Spatial structure and informational asymmetry in the economics of multiple stock renewable resources

Guillermo E. Herrera

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

University of Washington

2001

Program Authorized to Offer Degree: Department of Economics

UMI Number: 3013969

UMI®

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

University of Washington

Graduate School

This is to certify that I have examined this copy of a doctoral dissertation by

Guillermo E. Herrera

and have found that it is complete and satisfactory in all respects, and that any and all revisions required by the final examining committee have been made.

Chair of Supervisory Committee:

Gardner Brown

Reading Committee:

Gardner Brown

Richard Hartman

Ray Hilborn

Date: June 8, 2001

University of Washington

Abstract

Spatial structure and informational asymmetry in the economics of multiple stock renewable natural resources

Guillermo E. Herrera

Chair of the Supervisory Committee:

Professor Gardner Brown
Economics

The open-access inefficiencies of renewable resources are heightened, and their regulation complicated, by heterogeneous stock composition, non-uniform spatial distribution, and informational asymmetries between regulators and those involved in resource extraction. These issues continue to provide fertile ground for theoretical and empirical research. The uncertainty inherent in the catch composition in multispecies fisheries, for example, has been largely ignored by the literature, though it has important implications for the efficacy and relative merits of different types of regulation. In this dissertation, I present two papers which extend the literature on multiple stock renewable natural resources.

In the first paper, I consider a two-species system in which the stocks are differentially distributed across space (or "depth"). I develop an analytical model as well as a

numerical algorithm for solving for optimal dynamic behavior, and show how the benefits of spatially structured regulation vary with economic and biological parameters as well as the distribution of stocks across space.

In the second paper, I consider incidental harvest, or "bycatch" as a stochastic process and allow for discarding of catch, an issue not yet addressed in a dynamic setting. I describe the strategic interaction between a social planner and two different types of harvesters, one of which imposes a "technological externality" on the other. Using a disaggregated or "representative agent model," I compare the relative performance of various regulatory instruments meant to control bycatch and discarding: price instruments, vessel quotas (trip limits), and value-based quotas. I show that the relative performance of these instruments depends upon various factors, including the nature of the bycatch process, differences in the market (ex-vessel) prices of the stocks, the relative efficiency of the two types of harvesters, and the magnitude of fixed costs associated with resource extraction.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acknowledgements

I thank Gardner Brown, Dick Hartman, and Ray Hilborn for their advice during this process. I have greatly benefited from and appreciated their patience, wisdom, and breadth of perspective. Eugene Silberberg has been my inspiration in teaching. Thanks to Brett Berger and Karl Seeley for their many helpful comments, companionship, and mutual commiseration. Husky Racing, in particular teammates Scott Chegwidden, Paul Johnson, and Greg Lipski, enriched my graduate school experience immeasurably and lent it much-needed perspective. Finally, I thank Jerry Chow for all her assistance, support, and understanding.

Dedication

To Libby and Guillermo
for their strength, support, and friendship

INTRODUCTION

The inefficiencies associated with many commercial fisheries have long been described as a problem of open-access, or lack of ownership. R. Scott Gordon's seminal paper echoes Garret Hardin's (1968) bleak prognosis for the outcome of open-access resource exploitation: When average rather than marginal productivity is used as the criterion for entry, benefits are equated with opportunity costs for all participants; all rents are thus lost from the system and "the fishery, a rich and self-renewing resource, almost invariably provides a poor livelihood for the great bulk of those engaged in its exploitation" (Gordon 1954).

The role of the regulator (or "benevolent social planner") is to counteract the tendency towards rent dissipation. In a dynamic context, the regulator seeks to manipulate harvest rates and/or stock levels so as to maximize the discounted flow of social net benefits arising from a resource. Colin Clark (1990) and many others in his footsteps have approached the regulator's problem in the case of a single species with logistic growth as a control theoretic exercise, with current-value Hamiltonian

$$(1) \qquad H = ph(E, X) + \lambda\left[rX(1 - X/K)\right].$$

Here h is the harvest at a given instant in time, a function of effort E and biomass X; r is the intrinsic (or maximum *per capita*) growth rate of biomass, and K the carrying capacity of the available habitat.

The co-state variable, λ, represents the shadow value, or *in situ* value of the stock, and is the central focus of regulatory policy (or at least regulatory policy with an economic foundation). In the single-species model with commonly used Schaefer harvest function (where h is linear in both E and X), the optimal behavior is "bang-bang" due to the linearity of the model, and hinges critically upon the relationship between λ and the *ex vessel* price (p) of the resource: Harvest effort is maximized when the price of the resource exceeds the shadow value, and zero when the reverse is true. These all-or-nothing responses drive the stock as rapidly as possible towards a "dynamic steady-state" stock level, at which $\lambda = p$ and effort is exerted at some constant rate in perpetuity (cf. Clark 1990 pp. 39ff; Brown 2000 pp. 881-2). Economists tend to view renewable resources as capital; the appropriate marginal decision is whether to leave a unit of capital *in situ* to appreciate[1], or to extract it and invest the proceeds at a market rate of interest.

In theory, and in a deterministic world, open-access resources can be regulated via several different mechanisms which are ostensibly equivalent: Controls on inputs to

---

[1] Or, more generally, to provide an increased flow of services in the future. These services could include increased consumption from future extraction of a commercial stock, or they could take the form of existence values and ecological services over time. For example, Hartman (1976) shows how a flow of non-extractive benefits arising from a renewable resource can fundamentally alter the optimal extraction rate and, indeed, the decision whether to harvest at all.

production (i.e. E), limits (quotas) on the harvest rate h, minimum escapement requirements, and taxes on landed catch can all be used to elicit the optimal behavior contingent on the social benefits (the *ex vessel* price p) of harvest and its social opportunity cost.

Historically, however, efforts to curtail the devolution towards rent dissipation and economic and biological overexploitation have been fraught with difficulties (cf. Wilen 2000). Harvesters, for example, may adhere to the letter of a law constraining "effort" in the form of number of vessels, but expand effort by increasing the size or steaming power of the remaining vessels. Efforts to reduce harvest mortality by reducing catchability, or vulnerability to fishing gear, may achieve biological productivity goals but do not solve the problem of rent dissipation. A combined approach, i.e. limiting the technology used as well as *how much* of that technology is used, has been employed to good effect in some cases (e.g. in the Maine lobster fishery, restricting harvest technology to traps, in addition to restricted entry and a limit on the number of traps employed by a given participant). Economic instruments, favored by economists in many contexts, have political and equity implications that may make them unpalatable to policymakers; these political costs may outweigh efficiency gains of these policies, though this is an empirical question that has been given little attention.

The regulatory problem in fisheries (or open-access resources generally) can be viewed as a principal-agent problem, in which the harvesters (agents) act to maximize perceived private rents in response to regulatory constraints imposed by the regulator (principal). The problem is made more complex in the fisheries arena by a high degree of uncertainty regarding the costs and benefits experienced by agents, as well as by the physical separation of principals (bound to shore) and agents (who act at sea). The need for the regulator to base regulations in most cases on landed catch (production output) rather than on what happens at sea gives harvesters leverage with which to extract private informational rents. The strategic interaction pushes the system into the interior of the continuum between social rent maximization and open-access rent dissipation.

The need to incorporate the response of harvesters to regulations and economic incentives in general has received considerable attention in the literature. A number of papers address spatial movement of harvesters, or spatial patterns of effort allocation, in response to differences in perceived catch (Opaluch and Bockstael 1984; Allen and MacGlade 1986; Defeo, Sedo et al. 1991; Fahrig 1993), the dynamic evolution of the level of effort in response to rents (Yew and Heaps 1996), and the evolution of different types of harvesters filling different "ecological" niches (McKelvey 1983).

In systems where stocks are homogeneous (single species, uniform size/age, and uniform quality), harvesters generally retain all the catch they withdraw from the system, so there is a fairly good correspondence between what the regulator observes on land and what occurs at sea. The deleterious consequences of informational asymmetry and resultant strategic interactions are amplified in systems with heterogeneous stock (e.g. multispecies or multiple size classes) or when there is spatial heterogeneity in the biological or economic productivity (shadow value) of the stock. In these cases, the range of behaviors in which harvesters can engage expands, and the tension between private and social objectives may be increased.

In systems consisting of multiple stocks[2], the regulatory strategy is in essence similar: withdraw units of biomass for which price exceeds the shadow value, and retain as natural capital those which are more valuable *in situ* than in the market. However, stocks in these systems are frequently linked either ecologically or technologically. Such linkages cause the shadow value of each stock to depend upon the level of the other stock, complicating management prescriptions: The regulator must not only decide how much effort is to be exerted in the system, but also how much of each stock is withdrawn, and by whom.

Ecological linkage can take the form of predator-prey interactions, competition, or other forms. For two stocks following logistic growth, a common representation of ecological interaction is linear in both stocks. For example, if X and Y grow logistically when independent of one another, their joint dynamics can be characterized by a variation on (1):

---

[2] I will refer to these as "multispecies systems," though most of the discussion below could apply to a single species with heterogeneous age, size, quality, or sex composition.

$$(2)\ \dot{X} = r_X X\left(1 - X/K_X\right) + \alpha XY; \quad \dot{Y} = r_Y Y\left(1 - Y/K_Y\right) + \beta XY$$

Parameters values $\alpha > 0$, $\beta < 0$ would represent a predator-prey relationship between X and Y respectively; if both interaction parameters are positive the relationship is mutualistic.

A number of authors have explored the bioeconomics of ecologically linked systems and the optimal use of separate harvest of two substocks, either when mixed equally in space (Beddington and May 1980; Mesterton-Gibbons 1988; Clark 1990; Mesterton-Gibbons 1996; Hoagland and Jin 1997) or when the stocks occupy a spatially structured habitat (Supriatna and Possingham 1999). I do not consider ecological further in this dissertation, though it would not be difficult to incorporate such a relationship into my analysis.

In the absence of ecological interaction, species can be linked technologically via nonselective harvest gear. Spatial correlation between substocks and the inability of harvesters to see and manipulate what they are catching makes coincidental harvest nearly inescapable in multispecies fisheries (Kirkley and Strand 1988; Alverson, Freeberg et al. 1994; Hall 1996; Alverson 1999). Whether the inextricability of catch composition is socially undesirable depends on economic parameters, current stock levels, and the value derived by society from a unit of stock harvested by a particular agent. Clearly it is undesirable for a harvester to withdraw (and kill) a unit of biomass for which they have little or no value but which is of great market or existence value to some other group. In other instances, however, the ability to catch multiple species is a useful type of joint production and need not be regulated. In many systems, the ability of harvesters to catch more than one stock decreases volatility in welfare, and attempts to disaggregate catches would have severe welfare implications (Wilson 1982; Fletcher, Howitt et al. 1988; Vestergaard 1999).

The harvest of biomass of a stock other than the "intended" stock is defined as incidental catch, or "bycatch," though definitions of bycatch vary widely across the discipline. Boyce (1996) uses the three subtly different definitions "the incidental take of a species that has value to some other group," "incidental harvesting of nontargeted species," and "incidental catch in a fishery for which there exists another constituency with a claim on the bycatch species". The first of these definitions suggests an economic externality associated with bycatch, the second hinges on the "intentions" of the harvesters, and the third is rights-based. Boyce is not the only source of confusion regarding the definition of bycatch: McCaughran defines the term as catch of "non-target" species, whether retained or discarded (McCaughran 1992), while Hall (1996) eschews this definition in favor of "that portion of the capture that is discarded at sea dead." This latter definition of "bycatch" is what most of the literature refers to as "discard mortality."

If bycatch is defined, say, as "the socially undesirable removal of a species other than that nominally/officially targeted," then the social desirability of bycatch prohibition is a truism. By most other definitions, however, prohibition of bycatch would be an economic blunder; since incidental catch is inherent in the operation of most commercial fisheries, bycatch prohibition would mean prohibiting targeted catch as well. Bycatch, even if it has positive social costs *per se*, is much like most types of pollution, in that there is likely to be some internal optimum where costs and benefits are equated on the margin.

Complicating the equation further is the ambiguity of the concept of "target species." In many fisheries the "target catch" is in fact a mix of two or more species; if the target species is defined as that which constitutes the bulk of the catch value, then in many instances harvesters operate with the knowledge (and hope) that they will experience "bycatch;" the ability to retain "nontarget" biomass may be critical to the profitability of their operation. Such semantic issues permeate the bycatch and discarding literature, and make suspect such policy prescriptions as "bycatch minimization" or even "bycatch reduction." Some authors avoid the terms altogether, referring rather to jointly optimal dynamic harvest of two or more species (cf. Fletcher, Howitt et al. 1988; Squires and Kirkley 1991; Mesterton-Gibbons 1996). Wilson (1982) in particular questions our ability to manage species atomistically and – given the inherently multipurpose nature of artisanal fishing fleets such as that in the Gulf of Maine – advocates a holistic, system-wide approach.

The regulatory approach to bycatch is complicated by the possibility of discarding of harvested biomass before returning to port. The vast majority of discarded organisms dies, due to damage sustained interacting with fishing gear or to rapid changes in depth which organisms cannot survive (Natural Resource Consultants 1990; Boyce 1996). Due to informational asymmetries and the need to base controls on biomass brought to shore, a new dimension is added to the regulator's problem: Even if bycatch is undesirable *per se*, stringent controls on *retained* bycatch may not reduce bycatch at all, but may instead simply increase the rate of discarding, exacerbating the existing inefficiency. The agent, confronted with a limitation on retained bycatch, either reduces bycatch rates or increases discard rates, whichever is most profitable. The possibility of discarding necessitates, in general, the granting of additional informational rents[3] to harvesters.

Species are often not uniformly distributed across space, and managing them as if they were can lead to suboptimal results. In single-species systems, biomass often exists as a metapopulation. That is, it comprises more or less distinct substocks connected, to varying extents, by migration or other dispersal mechanisms (Caddy 1975; Underwood and Fairweather 1989; Day and Possingham 1995; Brown and Roughgarden 1997). If

---

[3] The rents I refer to here are those perceived by the harvesters in the short run. The nature of the tragedy of the commons is that harvesters in open-access contexts strive to maximize short-run rents even though their collective behavior serves to diminish their long-run welfare.

different substocks tend to be net contributors to other stocks, then the *in situ* value of biomass in these patches is higher than that from other locales. Differential (and directional) productivities call for heterogeneous harvest rates; uniform price instruments (e.g. taxes) or quotas do not cause harvesters to adequately internalize disparities between shadow values and private values. Several studies have investigated open-access (Sanchirico and Wilen 1999) and optimal (Tuck and Possingham 1994) harvest patterns of effort in a metapopulation setting, some with counterintuitive results: Brown and Roughgarden (1997), for example, show it is optimal under some conditions to sharply curtail or even eliminate harvest from all but one patch in a barnacle metapopulation.

Heterogeneity of shadow values across space extends into a multispecies setting, with interesting implications. If stocks in a multispecies system have different spatial distributions, effort controls become problematic, as a unit of effort may be exerted in an area where bycatch rates are high or low. Similarly, a single price instrument applied to one stock is not appropriate for stock withdrawn from all points in space, because withdrawal of stock from one location may imply very different ecological or technological externalities than that withdrawn from elsewhere.

The goal of this dissertation is to address to deficiencies in the literature dealing with multispecies systems, bycatch, and discarding: The possibility of utilizing information about spatial distribution of species to construct spatially structured input (effort)[4] controls, rather than simply closing certain areas to harvest altogether; and the implications of uncertainty regarding bycatch rates for policy. Under deterministic assumptions the regulator can use a number of different policies to equal effect, but stochastic bycatch rates give rise to disparities between the performance of different instruments.

The dissertation is presented in two main papers to address these two issues. In the first paper, I first summarize issues of spatial heterogeneity and their treatment in the literature. I then present a model – the "Proportional Depth Model," or PDM – of a two-stock resource in which the stocks have different distributions across a simple representation of space. I develop the analytical results forthcoming from this model, then carry out simulations to assess the gains from spatially structured controls relative to aggregate controls on harvest effort. This portion of the dissertation seeks to extend the use of biological or ecological knowledge about multispecies resource stocks in order to improve the efficiency with which they are utilized.

---

4 While recognizing that the more common economic approach is to control either outputs (e.g. in the form of harvest quotas) or to use economic instruments, I focus on effort here because it is easier to control effort spatially than it is to implement spatially structured quotas or price instruments: landed stock looks the same regardless of its spatial origin, whereas regulators are increasingly able to monitor the spatial movements of harvesters.

In the second paper, I address the management of a system in which bycatch occurs as a stochastic process, and discarding is possible. I summarize the existing research relevant to this problem, though no literature currently addresses stochastic bycatch and discarding in a dynamic setting. I present my model and the analytical description of harvester behavior under various forms of regulation, then develop a stochastic dynamic programming model – vaguely similar to that used by Androkovich and Stollery (1992) – to analyze the relative performance of different bycatch control instruments. Through a more thorough understanding of the game-theoretic, or strategic, interplay between regulator and harvester, it is possible to evaluate alternative methods of reconciling private and public incentives, and to determine in which types of systems a shift in regulatory paradigm might be most cost-effective.

PAPER I. SPATIAL REGULATION IN MULTISPECIES SYSTEMS

A. Problem statement and review of literature

A sizeable body of literature views multispecies systems as a dynamic whole and attempts to optimize harvest effort over time to maximize the discounted flow of social net benefits. In such multispecies models, optimization of harvest may be complicated by ecological linkages between species. Species can be linked via Lotka-Volterra type predator-prey relationships, competition, parasitism, mutualism, etc. Through these relationships, harvest of one species impinges upon the dynamics of others.

Even in the absence of ecological linkages between species, the management of multispecies resources is complicated by technological linkages borne of nonselective effort. Effort ostensibly focused on one species impacts the dynamics of other species through incidental catch. A regulator would ideally view the mixed-stock resource as a system with multiple state variables, and take into account all equations of motion when determining the optimal effort level. Approach paths to equilibrium can no longer take the simple form of the Schaefer model, since one stock's "most rapid approach" may interfere with another's.

Because the regulator cannot observe the actual catch composition in most cases, regulation must either be based on what the regulator *believes* is being caught, or otherwise provide incentives so harvesters choose an efficient catch composition. In addition to direct observation[5], advances in technology can increase the set of feasible (i.e. enforceable) regulatory instruments. In particular, the regulator's ability to measure the location and intensity of effort reduces the information deficit of regulators, allowing them to more effectively discourage rent dissipation. Such technologies should in theory improve the efficiency with which resources are exploited, but the relevant policy question is how large these gains are in a particular case.

When organisms are distributed heterogeneously across space, first-best regulation takes into account their spatial distribution as well as the response of harvesters to this distribution. A number of studies consider the exploitation of a metapopulation, a set of sub-populations, or patches. These models take into account the separate dynamics of the sub-populations, as well as the transfer of organisms between patches, to derive the optimal spatial distribution of fishing effort (Tuck and Possingham 1994; Brown and Roughgarden 1997; Sanchirico and Wilen 1999). Studies have shown harvesters do respond to differences in expected catch as well as the spatial pattern of harvest costs when deciding where and how much to fish (Hilborn and Kennedy 1992).

---

[5] In many important commercial fisheries, such as the North Pacific Groundfish resource, the regulatory agency (e.g. NOAA and the National Marine Fisheries Service) expends considerable resources on direct observation of harvester behavior in order to both enforce regulations and better understand stock dynamics and the behavior of harvesters.

The management of the canonical single-species renewable resource has been extensively studied, starting with Beverton and Holt's (1957) seminal work and culminating with that of Colin Clark (1990). The Schaefer model assumes a single species is homogenous in biology and its distribution across space. I discuss the results from this simple model briefly here insofar as they provides a useful analog to the multispecies model I develop in subsequent sections. Biomass obeys a logistic growth function, and harvest is linear in both stock size and the effort level (cf. Clark 1990, p. 15): the equation of motion is $\dot{X} = rX(1 - X/K) - qEX$, where X is the biomass, r is the intrinsic growth rate of the stock, K is the carrying capacity of the population, and q is the catchability coefficient of the stock.

Given the equilibrium condition for the Schaefer model, it is easy to derive the constant effort level which maximizes sustained rents. This "static optimum" is a good approximation of first-best use of the resource if the discount rate is zero, i.e. if the transition to the steady-state is ignored. When the discount rate is positive, the approach to the steady-state is important; the static rent-maximizing solution is therefore a "dubious optimum" (Clark 1990, p. 30). The single-species Schaefer model can be readily solved as a dynamic optimization problem, with current value Hamiltonian as a special case of that given in (1):

$$(3) \qquad H = pqEX - wE + \lambda\left[rX\left(1 - \frac{X}{K}\right) - qEX\right]$$

where p is the (constant) *ex-vessel* price and λ is the shadow value, or *in situ* value, of a unit of stock. The catchability coefficient, q, reflects the vulnerability of the stock to harvest effort. Setting the time derivatives in the first-order conditions arising from (3), as well as the equation of motion for X, to zero yields the steady-state levels of stock, effort, and shadow value for the dynamic optimization problem. With costless effort ($w = 0$), the steady-state values satisfy

$$(4) \qquad \lambda = p; \quad E = \frac{(r+\delta)}{2q}; \quad X = \frac{K}{2}\frac{(r-\delta)}{r}$$

The steady-state effort ("singular") level is higher, and the stock level lower, for the dynamic case than for the static case. A positive discount rate raises the opportunity cost of holding stock *in situ* and makes it optimal to substitute out of stock and into capital.

In the Schaefer model, linearity of the objective function in the control makes it optimal to follow a "most-rapid approach path:" If the stock level is above (below) the steady-state level then it is optimal to harvest the stock as quickly (slowly) as possible until the stock level reaches the optimal steady-state level, then switch to the singular control.

Models of multispecies systems do not yield as easily to the analytical methods described above, though a number of authors have undertaken analysis of these systems. The problem of multispecies resources harvested with nonselective effort has been addressed for both independent and dependent species.

Clark (1990) develops a bioeconomic analysis of multispecies systems with a range of characteristics. For the system with two ecologically independent species, which yields "straightforward generalizations of the single species model," Clark argues a steady-state for the dynamic optimum must exist. However he states that "economic interpretation of this solution does not seem obvious" and does not attempt to determine an analytical solution for the steady-state or the nature of the optimal approach to this steady-state. The primary difficulty with solving these systems for an optimal time path of effort is that, with a single nonselective effort, it is impossible to guide one stock to its desired steady-state value without undesirable impacts on the other stock (Clark 1990, p. 318).

The independent species system is further analyzed by Chaudhuri (1986, 1987) and by Mesterton-Gibbons (1987). These analyses find a steady-state for the dynamic optimization problem, but their solutions are highly complex and difficult to interpret, and the exact nature of the approach path to this equilibrium is not determined.

Clark mentions the interdependent species system briefly, but does not attempt a full dynamic optimization. Mesterton-Gibbons (1988, 1996) carries out the analysis for the interacting species case (a general linear interaction term which can capture an array of biological relationships). These papers solve for the steady-state, or singular control, which satisfies the conditions for an optimum. This steady-state is exceedingly complex and does not readily yield economic intuition (see Mesterton-Gibbons 1996, Eq. 25 and Table 1). Hoagland and Jin (1997) partially solve the generalized interacting-species case in the special instance where one species has commercial value and the other has existence value, and Pascoe studies a case in which mitigating bycatch of a threatened commercial species may be more costly than leaving this stock unprotected (Pascoe 2000).

Ragozin and Brown (1985) study the optimal exploitation of a predatory-prey system in which only one of the two species was available to harvest ("catchability" $q = 0$ for one of the species). They conclude that following a disturbance that drives stocks below their optimal steady-state levels, it may in fact be optimal to harvest one of the species further before allowing the system to recover.

When selective effort is feasible, it is more straightforward to solve for the singular control in the case of multiple ecologically linked species. Clark solves for the "doubly singular control" in a system where there are biological linkages but where effort is perfectly selective, i.e. there is no technological interdependence between species (Clark 1990, p. 325). Perfect selectivity of fishing effort is an implausible assumption in most fisheries, simply because of the physical commingling of organisms.

None of the models described above combine both the elements of spatial structure and nonselective effort; in fact these two characteristics are likely to be present in many important renewable resource systems. Several species in the West Coast Groundfish Resource, for example, are shown to have different distributions across space; within species, there is frequently "ontogenetic bathymigration," or change in settlement depth with age, that might have important implications for management. Jacobson et al. have studied the age-specific distributions across depth of various species in the West Coast Groundfish Resource. The "bathymetric demography" of these species implies that effort-at-depth affects size structure, and hence reproductive capacity of stocks (Jacobson and Hunter 1993; Jacobson and Vetter 1996; Jacobson, Brodziak et al. 1997). While it is not included in the present model, it would be useful in the future to include at least a reduced form representation of size distribution in this analysis.

In the following section I develop the Proportional Depth Model, in which two species are technologically linked, but differently distributed across space. Their spatial distributions provide the regulator with a lever for improving the selectivity of harvesting, and at the same time are a source of informational asymmetry, as described below in Section C. For simplicity I assume full retention of all biomass withdrawn from these systems, i.e. I do not consider the possibility of discarding in the following section; this might be a useful complexity to add to the model in the future.

B. The Proportional Depth Model (PDM)

The Proportional Depth Model (PDM) is developed to investigate the potential benefits of using spatial distribution as a lever for increasing the selectivity of effort and the efficiency of regulation. To this end, the simplest possible scenario is used that contains the key elements of (a) multiple species, (b) spatial heterogeneity across species, and (c) the potential for spatially structured harvest effort.

The PDM depicts a system in which two ecologically independent species have different distributions across two discrete "depth" strata[6]. The behavior of the model is analogous in many respects to that of the single stock Schaefer model. Species evolve independently according to a logistic growth function. Both species are subject to nonselective harvest effort at either (or both) depth stratum; the harvest function at each depth stratum is linear in the stock at that depth and the effort exerted at that depth stratum.

Each stock in the PDM evolves independently according to a logistic growth function. In the absence of harvest, the biomass of stocks X and Y have the respective equations of motion

$$(5) \qquad \dot{X} = F(X) = rX\left(1 - \frac{X}{K}\right); \qquad \dot{Y} = G(Y) = gY\left(1 - \frac{Y}{L}\right).$$

---

[6] Or, more generally, across any spatial continuum. The description of this model presumes that the stocks are distributed vertically along a depth continuum, but the entire approach could easily be applied to other spatial distributions and could serve as the basis for area closures or area-specific harvest constraints.

Intrinsic growth rates of X and Y are r and g respectively, with corresponding carrying capacities K and L. Note that the dynamics of these stocks do not impinge upon each other.

The habitat occupied by species X and Y consists of two depth strata, Depth 1 and Depth 2. At any given time, the species-specific fractions c and d of stocks X and Y respectively are at Depth 1, and the remainder of these stocks at Depth 2. It is assumed that these proportions are constant, regardless of the biomass of the stocks; the stocks instantly reassort themselves so as to restore the depth proportions following any growth or harvest of the stocks in either depth stratum[7]. This assumption greatly simplifies the dynamics of this system and makes analytical treatment feasible; more realistic relaxations of this assumption can be incorporated into the numerical dynamic programming analysis discussed below.

Without loss of generality, I assume that, in relative terms, species X is the shallow-water species and Y is the deep-water species. That is, it is assumed that $c > d$ in the discussions of the mathematical results that follow[8]. The designation of X and Y as

---

[7] A more realistic representation of this system would allow for a temporary persistence of changes in the depth distribution caused by removals. This would greatly complicate the analysis, requiring a system with four state variables instead of two.

[8] Note that it is *not* necessarily the case that $c > 0.5$ or $d < 0.5$. In the West Coast Trawl Fishery application discussed in Section E, for example, $0.5 > c > d$.

shallow- and deep-water species respectively is arbitrary, and could be reversed without any qualitative change in the results. Some of the analytical results presented below – e.g. equation (17) are undefined if stocks are perfectly correlated across space, i.e. if $c = d$. In this case, spatial distribution of effort would have no impact on the selectivity of harvest effort; this scenario is discussed in the numerical results of Section E below.

Table 1 gives a description of the biological and economic parameters of the PDM. A schematic is shown in Figure 1: The rectangles represent the biomass of the stocks present at each of the two depths: cX and dY at Depth 1, and the remainders of X and Y at Depth 2. Stock-specific parameters are shown beneath each stock's stock column. Depth-specific parameters are shown to the right of the row corresponding to their respective depth stratum.

Harvest effort can be exerted in either of the two depth strata; effort levels exerted at Depths 1 and 2 are E_1 and E_2 respectively, and have respective marginal costs w_1 and w_2. These wages may plausibly be assumed to be zero if labor is compensated via a share system; considerable attention is given to the zero-wage case in what follows, because it is possible to achieve an analytical solution for the steady-state for this case. Harvest is linear in effort and stock as in the standard Schaefer model. In addition, the catchability coefficients of X and Y are q and s regardless of the depth stratum at which effort is exerted[9]. Species-specific harvest as a function of E_1 and E_2 is given by

$$
\begin{aligned}
&h_x(X,E_1,E_2) = qE_1(cX) + qE_2\left[(1-c)X\right] = qX\left[cE_1 + (1-c)E_2\right] \\
&h_y(Y,E_1,E_2) = sE_1(dX) + qE_2\left[(1-d)Y\right] = sY\left[dE_1 + (1-d)E_2\right]
\end{aligned} \qquad (6)
$$

Unless $c=1$ and $d=0$, or vice-versa, both types of harvest effort link the species technologically. Management of either species in isolation leads to suboptimal harvest of the other species.

The equations of motion for the two stocks in the face of efforts E_1 and E_2 are

$$
\begin{aligned}
&\dot{X} = F(X,E_1,E_2) - h_x(X,E_1,E_2) = rX\left(1-\frac{X}{K}\right) - qX\left[cE_1 + (1-c)E_2\right] \\
&\dot{Y} = G(Y,E_1,E_2) - h_y(Y,E_1,E_2) = gY\left(1-\frac{Y}{L}\right) - sY\left[dE_1 + (1-d)E_2\right]
\end{aligned} \qquad (7)
$$

Whether the stocks are present or extinct at the steady-state depends upon the intrinsic productivity of the stock and on the intensity of effort relative to the catchability, or vulnerability, of the stock to effort. In general, the steady-state level of X is positive if

---

[9] This assumption is reasonable if the same gear (e.g. a trawl) is being used to catch similar organisms at both depths; if in fact the fish of a given species differ between depths, e.g. small fish at Depth 1 and big fish at Depth 2, or if different gear (e.g. mesh size) is used at different depths, then it might make sense to have depth-specific catchabilities for each species. I do not consider this possibility in the PDM.

(8) (a) $cE_1 + (1-c)E_2 < \frac{r}{q}$,

and, symmetrically, Y is positive in equilibrium if

(b) $dE_1 + (1-d)E_2 < \frac{g}{s}$.

The stocks are positive in equilibrium for any effort pairing such that the depth-proportion-weighted total effort[10] does not exceed their biotechnical productivity, as defined by Clark (1990, p. 314-315). Extinction conditions as a function of effort are illustrated in Figure 2: In region I, efforts are low enough that both stocks are present at equilibrium. In region II, as deepwater effort E_2 gets high, the deepwater species (Y) is driven to extinction while X persists; in region III, Y persists but X is driven extinct; and in region IV efforts are high enough that both conditions in (8) are violated and both stocks are driven to extinction.

Solving the equations of motion (7) above, and taking into account the possibility of extinction, yields the steady-state stock functions

[10] This weighting by the depth proportion makes intuitive sense, since the proportion of the stock at a given depth represents the availability of the stock to fishing effort at that depth.

$$(9)\quad \begin{aligned} X_{SS}(E_1, E_2) &= \max\left[0, K\left\{1 - \frac{q}{r}\left[cE_1 + (1-c)E_2\right]\right\}\right] \\ Y_{SS}(E_1, E_2) &= \max\left[0, L\left\{1 - \frac{s}{r}\left[dE_1 + (1-d)E_2\right]\right\}\right] \end{aligned}$$

Steady-state stock levels in the PDM are reduced from their carrying capacities by a function of the efforts E_1 and E_2, i.e. by a sum of these two efforts weighted by the proportion of the stock at the corresponding depths. The potential extinction of one of the two species leads to kinked steady-state stock surfaces as a function of the effort pairing $\{E_1, E_2\}$. The higher the intrinsic growth rate of the stock the closer this steady-state stock level is to the carrying capacity; a higher catchability coefficient decreases the steady-state biomass.

There are limited benefits to exploring a "static analysis" of the PDM. As discussed in Section A above, static analyses are of "dubious optimality" because they implicitly assume a discount rate of zero. Basing policy only on the rents that arise at the steady-state ignores the potentially important stream of rents that are gained during the approach path to the steady-state. When the discount rate is in fact small, the static optimum is a reasonable -- and more tractable -- facsimile of intertemporally optimal behavior. It can for example indicate whether extinction of one (or both, in the extreme) species is likely to be an optimal outcome or the result of open-access exploitation.

The topology of steady-state revenue and cost in the PDM is analogous to that of the single-stock models of Colin Clark (1990, Ch. 2), as well as to those with two stocks and one nonselective effort (Mesterton-Gibbons 1996, 1987; Clark 1990 Ch. 10). The static analysis in the PDM is complicated however by the transition to a three-dimensional representation of costs and benefits, as well as by the possibility of multiple locally rent-maximizing actions, including corner solutions and extinction of one species.

For a given set of efforts-at-depth, $\{E_1, E_2\}$, the two-species system reaches equilibrium where $\dot{X}(X, E_1, E_2) = \dot{Y}(Y, E_1, E_2) = 0$. These conditions can either be met at an interior solution, or where one or both of the stocks are extinct, as dictated by the conditions in (8). The steady-state harvest level of stocks X and Y corresponding to a given effort pairing $\{E_1, E_2\}$ are, respectively,

(10) (a)

$$\begin{aligned} h_x^{SS}(E_1, E_2) &= h_x[X_{SS}(E_1, E_2), E_1, E_2] \\ &= \max\left(0, qK\left\{1 - \frac{q}{r}[cE_1 + (1-c)E_2]\right\}[cE_1 + (1-c)E_2]\right). \end{aligned}$$

(b) $$h_y^{SS}(E_1, E_2) = \max\left(0, sL\left\{1 - \frac{s}{g}[dE_1 + (1-d)E_2]\right\}[dE_1 + (1-d)E_2]\right).$$

Again, note the parallel between these steady-state values and that of the single stock Schaefer model. The steady-state harvest surface for a single species is a parabolic

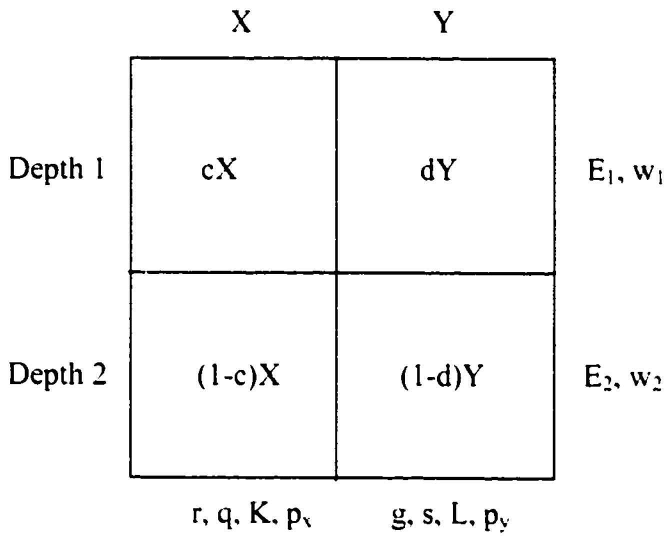

Figure 1: Schematic of two-stock system with proportional depth distributions.

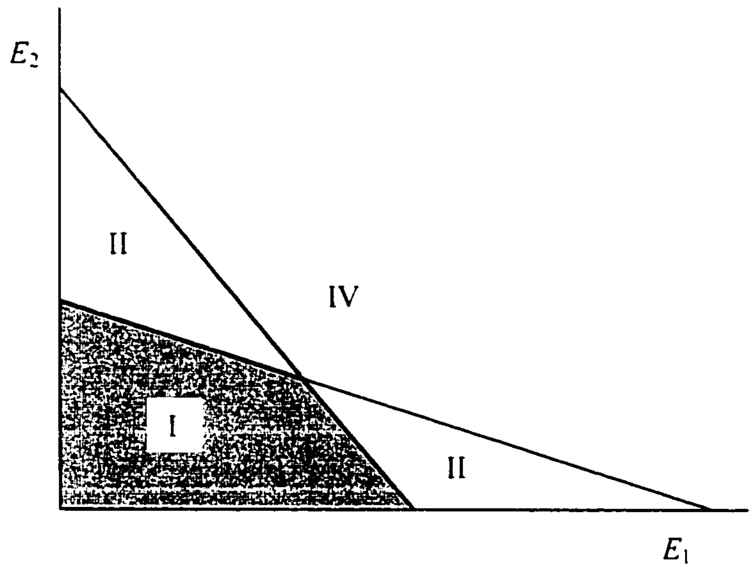

Figure 2. Effort pairings and the steady-state existence of two species.

sheet, as shown in Figure 3. Steady-state harvest of each species is bounded below by zero; harvest levels of zero correspond to extinction of the stock.

Instead of the yield-effort curve of the single-stock Schaefer model and the multispecies, non-selective effort models of Clark 1990 (Ch. 10), the PDM presents a yield-effort surface, whose height at any given effort pairing is equal to the market value of the harvest of the two stocks at equilibrium. The yield-effort surface for the PDM consists of three separate lobes corresponding to the extinction regions described y (8) and represented in Figure 2. Figure 4 shows a three-dimensional revenue-effort urface for a representative parameter set. If species X and Y have constant prices p_x and p_y respectively, the steady-state revenue arising from effort pairing $\{E_1,E_2\}$ is

(11) $$TR_{SS} = p_x h_x^{SS}(E_1,E_2) + p_y h_y^{SS}(E_1,E_2)$$

For the linear cost formulation[11] used in the model, total variable costs (TC) are depicted by the plane

(12) $$TC(E_1,E_2) = w_1 E_1 + w_2 E_2$$

[11] Most models in this literature abstract from fixed costs, although they may be significant. In Paper II of this dissertation, I explore the importance of fixed costs in another context.

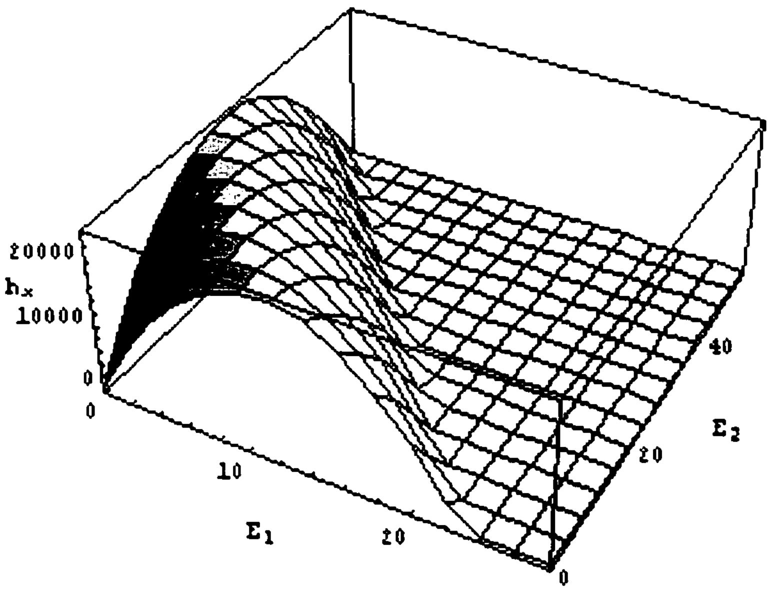

Figure 3. Steady-state harvest of a single-species as a function of depth-specific efforts E_1 and E_2.

As in the single-stock model, we expect rent dissipation in the PDM under open-access conditions. That is, harvesters continue to exert effort, at some depth stratum or combination of depth strata, until average net benefits become zero. The zero-rent condition (open-access outcome) can be seen graphically as an intersection between the steady-state revenue-effort of (11) and the cost plane (12). Since this intersection comprises a family of points, it is not immediately clear how the industry expands to dissipate rents under open-access. This question is not considered further here, as the point is question is the relative performance of two limited-entry scenarios, rather than limited-entry vs. open-access.

If there is an interior static optimum in efforts, this optimum is described by tangency(ies) between the revenue surface and cost plane defined by (11) and (12) respectively. Depending on the topology of the yield-effort surface, there could be multiple local maxima in steady-state rents: one on the "upper lobe" where both species are present (i.e. Region I in Figure 2) and possibly one on either of the "lower lobes" where one of the species is driven to extinction (Regions II or III in Figure 2).

The interior to the static rent maximization problem, where both species are present, is obtained by solving the system

$$(13)\qquad \begin{aligned} p_x \frac{\partial h_x(E_1.E_2)}{\partial E_1} + p_y \frac{\partial h_y(E_1.E_2)}{\partial E_1} &= w_1 \\ p_x \frac{\partial h_x(E_1.E_2)}{\partial E_2} + p_y \frac{\partial h_y(E_1.E_2)}{\partial E_2} &= w_2 \end{aligned}$$

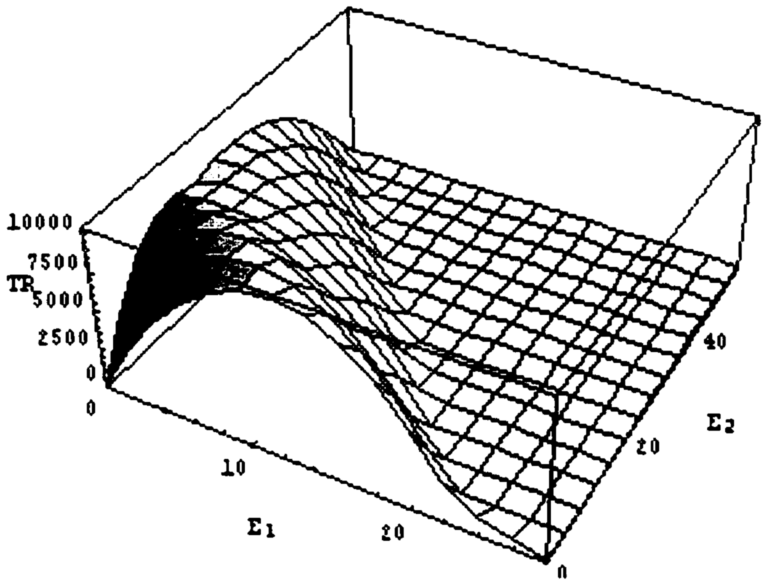

Figure 4. Static yield-effort surface for a 2-species Proportional Depth Model.

The value of the marginal product of each type of effort, i.e. the sum of the marginal revenues arising from each of the two stocks, is equal to the corresponding marginal cost of effort at the rent-maximizing effort pairing. Equation (13) is only a valid solution if the resultant stock levels are in fact positive for both species, i.e. if the existence conditions of (8) are satisfied.

The steady-state analysis is illustrative in some respects (extinction conditions and the general "shape" of the problem) but clearly this is a limited avenue for analysis. The interesting metric for management of a dynamic system is a stream of discounted net benefits over time. The static rent maximization is a valid description of benefits if the discount rate is zero; with no discounting, even the smallest difference in steady-state rents outweighs any difference in rents along the approach path.

As the discount rate increases from zero, the approach to the steady-state increases in importance; the net benefits accruing along the approach to equilibrium are less heavily discounted than the sustained benefits arising at equilibrium. The static optimum is no longer a legitimate basis for comparison of benefits of two policies, as discussed above. In general it is more interesting to presume some positive rate of discount, in which case the problem is cast as a dynamic optimization in two states and two control variables.

C. Dynamic optimization of the PDM

As in similar models treated by Colin Clark (1990), Mesterton-Gibbons (1996; 1987), and Chaudhuri (1986; 1988), the dynamic optimization for the PDM can only be solved analytically in the steady-state, and then only for the zero-wage case. Numerical solutions to the steady-state with positive wages are given below for a range of representative parameter values.

When depth-specific regulation is possible, the PDM presents a dynamic optimization with two states (the stocks, X and Y) and two controls (the depth-specific efforts E_1 and E_2). The current-value Hamiltonian for this problem is

$$\begin{aligned} H &= p_x qX[cE_1 + (1-c)E_2] + p_y sY[dE_1 + (1-d)E_2] - w_1 E_1 - w_2 E_2 \\ &\quad + \lambda\left\{rX\left(1-\frac{X}{K}\right) - qX[cE_1 + (1-c)E_2]\right\} + \theta\left\{gY\left(1-\frac{Y}{L}\right) - sY[dE_1 + (1-d)E_2]\right\} \end{aligned} \tag{14}$$

where λ and θ are the "shadow prices," or *in situ* values, of stocks X and Y respectively. Necessary first-order conditions for a maximization are:

$$\begin{aligned} H_{E_1} &= p_x qcX + p_y sdY - w_1 \le \lambda qcX + \theta sdY \\ H_{E_2} &= p_x q(1-c)X + p_y s(1-d)Y - w_2 \le \lambda q(1-c)X + \theta s(1-d)Y \\ H_X &= p_x q[cE_1 + (1-c)E_2] + \lambda\left[r - \frac{2rX}{K} - qcE_1 - q(1-c)E_2\right] = \delta\lambda - \dot{\lambda} \\ H_Y &= p_y s[dE_1 + (1-d)E_2] + \theta\left[g - \frac{2gY}{L} - sdE_1 - s(1-d)E_2\right] = \delta\theta - \dot{\theta} \end{aligned} \tag{15}$$

The first two first-order conditions (i.e. those with respect to the controls) in (15) are satisfied as equalities if there is an internal optimum in the corresponding effort; it is possible that a corner solution, in which one (or both) efforts are zero, is optimal.

At the steady-state for the optimum defined by (15), the two stocks and their shadow values must satisfy

$$\begin{aligned} &\dot{\lambda} = \dot{\theta} = 0 \\ (16) \qquad &\dot{X} = rX\left(1 - \frac{X}{K}\right) - qX\left[cE_1 + (1-c)E_2\right] = 0 \\ &\dot{Y} = gY\left(1 - \frac{Y}{L}\right) - sY\left[dE_1 + (1-d)E_2\right] = 0 \end{aligned}$$

Setting all of the time derivatives equal to zero, and assuming an interior solution $(E_1, E_2 > 0)$ in the first order conditions above, it is theoretically possible to obtain a steady-state solution in the six variables (E_1, E_2, X, Y, λ, and θ). This steady-state can be obtained analytically when the wage rates of effort are set at zero[12]:

---

[12] The zero-wage case is in fact a reasonable assumption if labor is compensated with a fraction of the value of the catch, or a "share," rather than a fixed hourly wage. In this case the harvester incorporates the share payments as a reduction in the ex-vessel price of harvest. However, the share paid to labor in such systems is endogenous, i.e. a decreasing function of the profits arising from harvest. In the short run it is reasonable to think share is fixed, but changing share in the long run is tantamount to a changing wage.

$$(17)\qquad \begin{aligned} &\lambda = p_x & &\theta = p_y \\ &X = \frac{K}{2}\frac{(r-\delta)}{r} & &Y = \frac{L}{2}\frac{(g-\delta)}{g} \\ &E_1 = \frac{s(1-d)(r+\delta) - q(1-c)(g+\delta)}{2qs(c-d)} & &E_2 = \frac{qc(g+\delta) - sd(r+\delta)}{2qs(c-d)} \end{aligned}$$

These steady-state conditions are analogous to those for the single-stock Schaefer model given in (4): The *in situ* prices for the two stocks are equal to their respective ex-vessel prices; the steady-state stock levels are exactly the same as in the single-stock case, i.e. they are equal to one half the carrying capacity (or the maximum sustainable yield stock level "X_{msy}") multiplied by a factor – less than unity – which reflects the level of discounting relative to the intrinsic growth rate of the stock.

The analogy of the effort levels is slightly more complex, but still intuitive: In the single-stock model, the steady-state effort level, or "singular control," is given for the zero-wage case by $E_{SS} = (r+\delta)/2q$. In the two-stock, two-control model, the structure of the steady-state effort is similar, but it takes into account the depth distributions of the two stocks and the technological linkages between them. In the case where the species are completely segregated by depth, i.e. $c = 1$ and $d = 0$, the effort expressions of (17) reduce to two separate single-stock Schaefer steady-states, as in (4), when the stocks have no spatial interaction.

With non-zero wages of effort, it is extremely difficult to derive an analytical solution to the steady-state conditions of (15), so I solve for the steady-state numerically in these cases. Results for a range of parameter values are given in Section E and compared to the results for the single-species and static cases.

The above analysis assumes that regulators have the ability to perfectly control the level of harvest effort[13]. If in fact they do not have this ability, then the spatial structure of the stocks ceases to provide a means of fine-tuning species composition. The following section describes the interaction between regulator and harvesters in the case where spatial controls are not feasible.

1. Depth-based regulation Vs. aggregate effort control

The ultimate goal of this research is to determine the potential benefits of implementing a new instrument, i.e. spatially structured effort controls. The new regulatory instrument should be adopted only if the marginal gains associated with depth-specific effort controls -- in terms of increased NPV deriving from the resource -- are sufficient to outweigh any fixed costs plus the present value of a stream of marginal costs associated with implementation and enforcement of the more discriminating policy instrument.

The regulator (principal) has different objectives than the harvester (agent): The principal strives to maximize the present value of a stream of social net benefits, while

---

[13] Or, less plausibly, the level of catch of each species coming from each spatial stratum.

the harvesters each try to maximize the present value of a stream of private net benefits. Indeed, in the extreme open-access scenario, where there are many harvesters and future ownership of the fruits of a system are uncertain, harvesters act as though the discount rate is infinite, i.e. they act so as to maximize *current* profits. This leads to a dissipation of rents arising from the resource, and a corresponding loss to society.

A strategic interaction between regulators and harvesters arises when aggregate effort restrictions are imposed upon the depth-structured resource. The following is a simple model of the incentives and decisions of harvesters in response to the regulation imposed upon them. In the PDM, the only choice variables the harvesters have at their disposal are the level of effort in each of the two depth strata. When the regulator imposes depth-specific harvest constraints, the regulation is completely specified. I assume harvesters comply with the regulation and exert exactly as much effort at each depth strata as they are allowed.

When the regulator cannot fully specify the actions of the harvesters, it is necessary to incorporate the reactions of the harvesters into the model of optimal regulation. Regulators first call out a maximum aggregate effort, and harvesters respond by choosing how to distribute this effort across space. This strategic game and the associated conditions for dynamic optimization of this system are described. Due to the linearity in the objective functions, harvesters in the PDM choose to exert all of their allotted effort at one depth, whereas the first-best exploitation would -- at least in some cases -- indicate a mix of efforts-at-depth.

Section C presents a methodology for the optimization of depth-specific effort levels in the Proportional Depth Model: The optimization of depth-specific efforts gives the highest feasible rents subject to the problem of non-selective effort[14]. In reality, regulation of effort-at-depth is costly, requiring initial capital investment and monitoring of effort location, which may or may not be feasible. If depth-specific effort control is prohibitively costly or unenforceable, the regulator must resort to a "blunt" regulatory instrument. In this section, I assume that the only instrument the regulator has at her disposal is the total amount of effort exerted (i.e. across all depth strata) [15]. The net benefits accruing under the blunt policy instrument are necessarily less than or equal to those arising under the more precise instrument, since the spatial effort control affords the regulator an expanded feasible set.

---

[14] The true first-best exploitation of this system would use perfectly selective efforts to target each species at each depth, as in Clark 1990, sec 10.3. Such a scenario is not likely to be feasible in most multispecies systems.

[15] Depth specific and aggregate effort controls are not the only instruments a regulator is likely to have at her disposal. Indeed in the West Coast Trawl Fishery discussed in Section F, a number of other regulatory instruments, such as trip limits and size limits, are used. Quotas (transferable or otherwise) could also be used, and in fact the whole analysis carried out here could be reproduced with a focus on quotas rather than effort restrictions.

With an aggregate effort restriction as the only available regulatory instrument, the exploitation of the PDM system takes place as a two-stage game: Regulators call out an aggregate effort constraint, and the harvesters choose an effort allocation across the depth strata so as to maximize their personal profits while complying with the constraint. Given a predictable response to the aggregate effort control they set, the regulators optimize the time path of aggregate effort so as to maximize the present value of societal net benefits.

2. The harvester's problem

In response to a constraint on aggregate effort of the form

(18) $$E_1 + E_2 \leq E_{reg}$$

the harvester strives to maximize profit (Π) in the current period, given by

(19) $$\Pi = p_x qX[cE_1 + (1-c)E_2] + p_y sY[dE_1 + (1-d)E_2].$$

Differentiating (19) gives marginal net benefits of E_1 and E_2 respectively:

(20) $$MNB_1 = p_x qcX + p_y qdY\,; \qquad MNB_2 = p_x q(1-c)X + p_y q(1-d)Y$$

Due to the linearity of the objective function in the two choice variables, it is clear that the harvester ends up at a corner solution, allocating all permitted effort at a given point in time to the depth stratum with greater marginal net benefits as defined in (20)[16]. The harvester chooses to exert

$$(21) \qquad E_1(E_{reg}) = \begin{cases} E_{reg} & MNB_1 \geq MNB_2 \\ 0 & MNB_1 < MNB_2 \end{cases}; \qquad E_2(E_{reg}) = E_{reg} - E_1(E_{reg})$$

If the marginal net benefits of the two effort types are equal then the harvester is indifferent as to the allocation of effort, so (21) is still an optimal strategy in this case.

3. *The regulator's problem*

The regulator is the leader, and the harvesters the followers, in this two-stage game. Suppose the regulator calls out the aggregate effort limit, E_{reg}. The harvesters respond to this constraint by allocating the allowed effort to the different depth strata, based on a maximization of current profits. In what follows, I assume that (a) there is excess capacity in this resource (i.e. the open-access level of effort $E_{OA} >> E_{reg}$), so that the aggregate effort constraint is always binding, and (b) harvesters act in ignorance of the long-term impacts of their harvesting decisions on the dynamics of the stocks.

---

[16] In a discrete time formulation of this model where stocks are drawn down during a given period, the optimal response function for the harvester would likely involve a combination of efforts. In the continuous time model, they are allocating a flow of effort over an infinitesimally short period, so no such draw-down takes place.

The regulator can predict the response of harvesters to the aggregate effort constraint, since she has perfect information about the objectives of the harvesters and all relevant parameters. In general, the harvesters respond to the aggregate effort constraint by allocating some amount of effort, $E_1^H(E_{reg})$ and $E_1^H(E_{reg})$ respectively, to Depths 1 and 2. Given these reaction functions, the regulator solves a dynamic optimization similar to the one described in Section C above, although now it is a problem in a single control variable, E_{reg}. That is, the regulator's problem under aggregate effort control has the Hamiltonian

$$
\begin{aligned}
H = {} & p_x qX\left[cE_1^H(E_{reg}) + (1-c)E_2^H(E_{reg})\right] \\
& + p_y sY\left[dE_1^H(E_{reg}) + (1-d)E_2^H(E_{reg})\right] - w_1 E_1^H(E_{reg}) - w_2 E_2^H(E_{reg}) \\
& + \lambda\left\{rX\left(1-\frac{X}{K}\right) - qX\left[cE_1^H(E_{reg}) + (1-c)E_2^H(E_{reg})\right]\right\} \\
& + \theta\left\{gY\left(1-\frac{Y}{L}\right) - sY\left[dE_1^H(E_{reg}) + (1-d)E_2^H(E_{reg})\right]\right\}
\end{aligned}
\tag{22}
$$

If the harvester's responses to E_{reg} were differentiable functions of the state variables, the regulator's problem could be solved by substituting the response functions (21) into (22) and then deriving necessary conditions. However, the response functions are clearly not differentiable so this problem does not yield to standard control theory techniques. To resolve the problem of the tendency of harvesters toward corner solutions in effort allocation, I have devised a procedure for determining which corner solution is likely to prevail at the steady-state.

4. Nash equilibrium in regulator-harvester interaction

I search for a Nash equilibrium in the interaction between harvester and regulator as follows: Since the harvester is presumed (see (21) above) to be at a corner solution, I solve the dynamic optimization for the regulator's problem assuming a given corner (i.e. either $E_1 = E_{reg}$ or $E_2 = E_{reg}$). Once a solution has been reached, I check to see if in fact the conditions for selection of that corner hold. If $E_1 = E_{reg}$ was assumed, I check whether in fact $MNB_1 > MNB_2$ at the steady-state. If so, the corner constitutes a mutual best response, or Nash equilibrium, to the game. The same process is repeated for the other corner.

Once both corners have been checked, four cases are possible: (i) both corners could be Nash equilibria, in which case the regulator would choose the corner yielding higher dynamic rents; (ii) only E_1 is a corner or (ii) only E_2 is a corner; in either of (ii) or (iii) the regulator would choose the corner yielding an equilibrium; or (iv) neither corner yields an equilibrium, in which case the game has no steady-state solution. In this last case the harvesters pursue an oscillatory path of effort, with one area's stocks being harvested down to a point before effort switches to the other area. This final case is likely to occur in cases where the stocks are highly differentiated by depth. In these cases harvesters do not settle at one corner in equilibrium. Instead, they harvest in one depth stratum for a period of time, during which they drive down the stock that predominates there. Eventually this stock becomes sufficiently depleted that they switch to the other depth stratum and harvest the other stock, which has had a chance to recover. This "pulse-harvesting" behavior leads to an *average* level of effort that is similar to what the regulator would choose under depth specific control, and therefore the spatial instrument does not yield much gain in these highly differentiated scenarios. This phenomenon is described in more detail in Section E (and depicted in Figure 7).

Due to the complexity of the PDM, I limit analytical treatment to the zero wage case; the following section briefly describes the numerical dynamic programming routine I have implemented to solve explicitly for the NPV-maximizing trajectories of efforts and stocks over for a given set of parameters.

D. Dynamic Programming solution of the PDM

The analytical treatments of the preceding sections are appealing in that they allow, in some cases, for derivation of general solutions to the optimization of effort in the PDM. However the complexity of the system makes analytical treatment of the system infeasible unless stringent assumptions about costs and other parameters are made. Indeed, even under these assumptions, it is not possible to derive an approach path, in contrast to the single-stock Schaefer model. With a positive discount rate, the approach path is likely to be an important part of any comparison of policy effectiveness.

In this section a dynamic programming algorithm is described which allows for explicit derivation of the approach path in the PDM (or a number of other related models), given a set of model parameters and starting stock levels. While this methodology does not provide an analytical solution for the approach path, it does provide a full time-path from the starting conditions to the steady-state, and suggests some interesting differences between the optimal approach path and the rule-of-thumb "practical approach paths" suggested by Colin Clark (1990) and Mesterton-Gibbons (1996). Dynamic programming allows for explicit calculation of the difference in Net Present Value (NPV) arising from different types of regulation.

The dynamic programming routine works backward from the final period of a finite time horizon. The time horizon and time step are set as a parameters. In each time period, the program iterates through a two-dimensional state space with a specified resolution. For each pairing of stocks, the two-dimensional control space is searched, again with a resolution specified as a parameter. The best effort pairing at time t, $\{E^*_{t1}, E^*_{t2}\}$, is chosen for each stock pairing such that

$$(23) \qquad \{E^*_{t1}, E^*_{t2}\} = argmax\ \{ V_t(X_t, Y_t, E_{t1}, E_{t2}) + V^*_{t+1}[X_{t+1}(X_t, E_{t1}, E_{t2}), Y_{t+1}(Y_t, E_{t1}, E_{t2})] \}$$

where V_t is the value of harvesting stock levels X and Y with effort levels E_{t1} and E_{t2}, at time t, and V^*_{t+1} is the optimized value of future harvests given current stock levels X and Y and effort levels E_{t1} and E_{t2}. If the stock pairing $\{X_{t+1}, Y_{t+1}\}$ is not in the stock array, the value is interpolated from the bracketing points in the value matrix, using a linear interpolation algorithm[17]. Once found, the optimal effort levels and the value arising from those effort levels are recorded in the spreadsheet.

In the terminal period T there is no future (salvage) value, so E^*_{T1} and E^*_{T2} are chosen as

$$(24) \qquad \{E^*_{T1}, E^*_{T2}\} = argmax\ V_T(X_T, Y_T, E_{T1}, E_{T2}).$$

The output of the backward simulator is a value array and control array for each point in time: the optimal effort for each depth stratum at each point in time is recorded as a function of stock levels X and Y.

The time path for any starting stock level is calculated by the forward simulator as follows: In each time period, the effort corresponding to the current stock levels is chosen. If the stock levels do not correspond to an element of the stock grid, then the optimal effort is calculated using a linear interpolation of the bracketing points in the grid. Given the chosen effort levels, new stock levels are calculated for the next step. This process repeats until the end of the time horizon.

As the end of the time horizon is approached and the future dynamics of the stocks become less and less important, it becomes optimal to "mine" the stocks. In a short

---

[17] The interpolation routine could easily be re-implemented using a second-order approximation of the curvature of the value surface, in lieu of the linear interpolation; visual inspection of the value surfaces generated suggests this would not significantly alter results.

time horizon, this behavior can significantly impact the NPV arising from the system and hence the validity of any comparison of policy effectiveness. If the time horizon is long enough or the discount rate high enough, then these boundary effects become insignificant.

E. Results

1. Numerical determination of steady-state of dynamic optimization

A "core parameter set" for the PDM is given in Table 2. These parameters depict two stocks moderately differentiated by depth: 70% of stock X is at Depth 1 while 40% of stock Y is at Depth 1. In addition, the shallow-water stock X is biologically more productive, both in its intrinsic growth rate ($r > g$) and its carrying capacity ($K > L$). In the core parameter set, both stocks have the same ex-vessel price and cost of effort does not vary with depth.

Numerical solutions to the steady-state of the PDM dynamic optimization are given in Table 3 for various parameters. The core parameter set is used a baseline, and variations from those values are given in the table. A comparison of steady-state controls and stock levels across different parameter sets yields results that corroborate economic intuition as well as the analytical results from Section C: an increase in the discount rate from 0.05 to 0.08 leads to an increase in both effort levels and a decrease in both stock levels at the steady-state; increasing the rate of time preference makes it optimal to substitute out of biomass and into capital. As the discount rate grows sufficiently high, we would expect to see one or both stocks driven to extinction. As wage rates increase together, less effort is exerted and higher standing stocks maintained; as relative wages change effort is shifted from one depth to another as expected.

2. Numerical policy comparisons

Benefits of depth-specific effort control in the PDM depends on parameter values as well as on the starting stock levels. I ran simulations with deviations from the core parameter set (Table 2) to investigate patterns in the benefits (NPV increase) due to spatial effort regulations as a function of parameter values.

Table 4 shows the effect of different parameters on effectiveness of spatial controls. For each parameter investigated, the table shows, in percentage terms, the maximum NPV gain and the mean NPV gain over the entire stock space. Panel (a) shows the impact of the degree of spatial differentiation on NPV gain; (b) shows the impact of the discount rate; (c) the impact of disparity in growth rates of the two species; and (d) the effect of price differential. Within any given parameter set, the NPV gains associated with spatial controls vary with starting stock levels. Table 4 gives the maximum NPV gain, in percentage terms, across all of the possible starting stock levels.

The benefits of spatial regulation are concave in the degree of spatial differentiation of the stocks, as indicated in Table 4a. With two stocks perfectly correlated in space, optimal "depth-specific" exploitation focuses all effort at a single depth stratum. Marginal product of effort is higher in the stratum in which both stocks are concentrated, and there is no benefit in terms of selectivity, to using a combination of efforts. Harvesters, in response to an aggregate effort control, also choose to exert all their effort in this same depth stratum. Figure 5a illustrates the stock trajectories (i) and optimal effort levels (ii) for a system of two identical stocks perfectly correlated ($c = d = 0.7$) across space. All effort is exerted at Depth 1, and both stocks are driven to the same level. Figure 5b shows the results under aggregate effort control; not surprisingly, the gains of spatial regulation in this case are zero.

As spatial differentiation of the stocks increases, optimal harvest involves a combination of efforts at the two different depths: Concentrating all effort at either depth implies a suboptimal harvest of the stock not concentrated at that depth. Figure 6a shows the stock and effort trajectories for two identical species where $c = 0.7, d = 0.45$. Under aggregate effort control, harvesters still find it optimal to exert all their effort at Depth 1, as indicated in Figure 6b. Doing so yields a higher current profit level; in addition, harvest pressure at Depth 1 keeps the level of the deepwater stock (Y) depressed, so that it never becomes optimal to switch to the other stratum. The effort level allowed by the regulator in the aggregate effort case is lower than the total effort allowed in the depth-specific case, since effort now carries with it an inefficiency not present in the first-best use.

When spatial differentiation is sufficiently extreme, a different phenomenon occurs that decreases the benefit of spatial regulation. Figure 7a shows the result of the extreme case in which stocks are completely contained in their respective depth strata, i.e. $c = 1$, $d = 0$. Under depth-specific regulation in this case, the regulator allows equal amounts of effort at each of the two depth strata; the levels of effort correspond to the solution for separate Schaefer harvest models. Under aggregate effort control, one might expect even larger gains than in the partially differentiated case of Figure 6. However, the extreme spatial differentiation causes there to be no "Nash equilibrium" to the game described by (21) and (22). Harvesters initially harvest in one stratum, but as they do so, they deplete the stock in this area. Coincident to this, the stock in the other area grows, unchecked because there is no technological linkage between the stocks. Harvesters at some point find it preferable to switch to the other area. Through this process, effort allocation by harvesters in the aggregate effort case oscillates between the two depth strata; Figure 7b illustrates this. The end result is that the *average* effort levels and stock levels under aggregate effort control are very similar to those under depth-specific effort control. Consequently the benefits of implementing depth-specific control in these cases is negligible.

The maximum NPV gain diminishes as the discount rate increases (Table 4b). This implies that the majority of the difference between the performance of the two policies arises further out in time. As the discount rate gets high, differences in NPV between the policies along the approach are given more weight. The NPV along these approach paths are more similar than the steady-state NPV.

Growth rate differentials between species also affect NPV gains: Table 4c shows maximum NPV gains diminishing as the disparity in growth rates gets large. When one stock's productivity gets sufficiently larger than the other's, it is optimal to fish only at the depth where the dominant stock is concentrated. A depth-specific effort control with all effort focused at one depth is more likely to coincide with the harvester's predilection for corner solutions. In systems with a highly dominant species (either a higher intrinsic growth rate or a higher carrying capacity), it is not likely to be cost effective to introduce spatially structured effort controls. Incentives of harvesters largely correlate with those of the regulator in these instances.

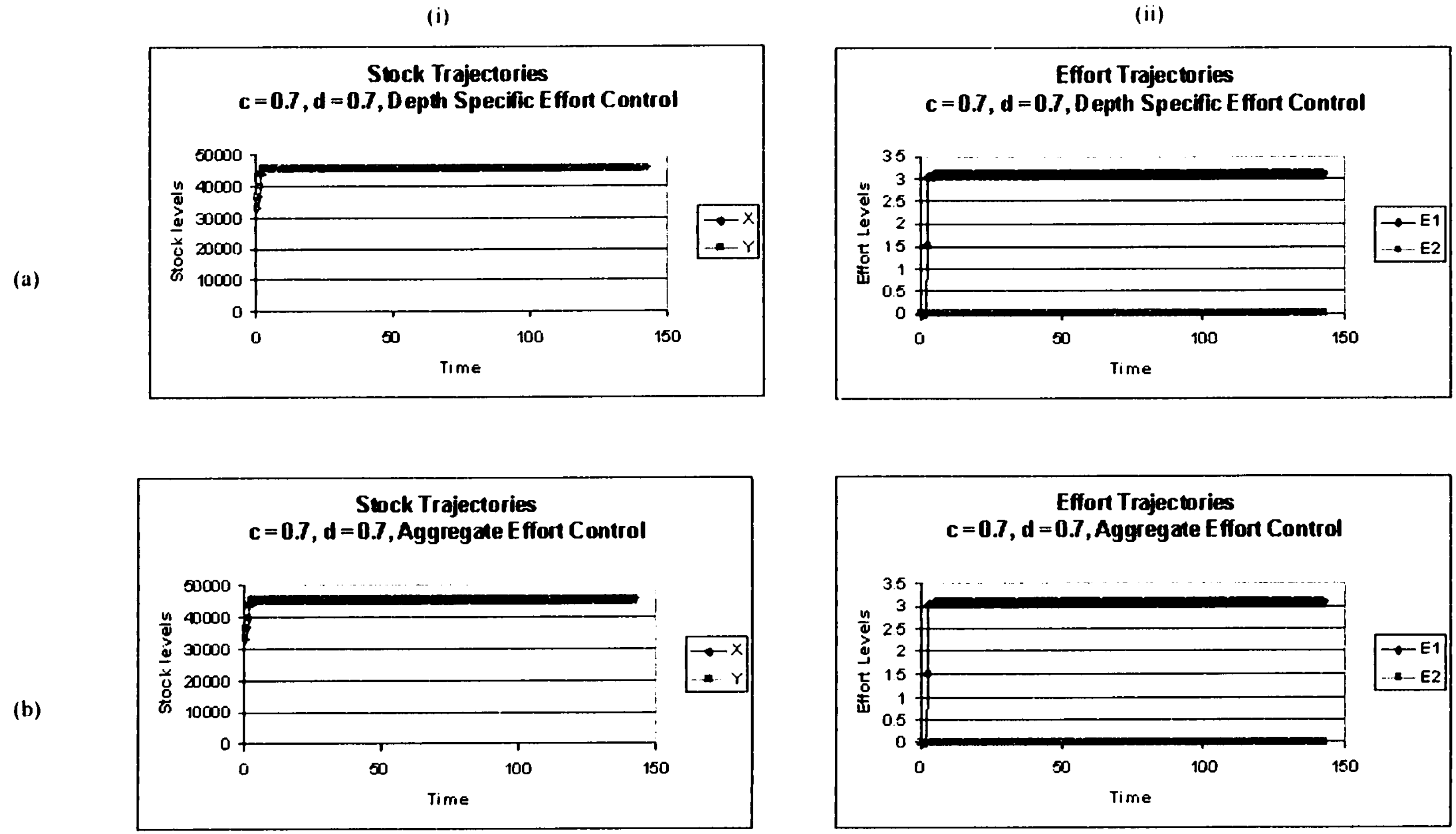

Figure 5. Stock and effort trajectories for the PDM under Depth-Specific (a) and Aggregate (b) effort controls. Stocks have identical depth distributions, with 70% of each of *X* and *Y*

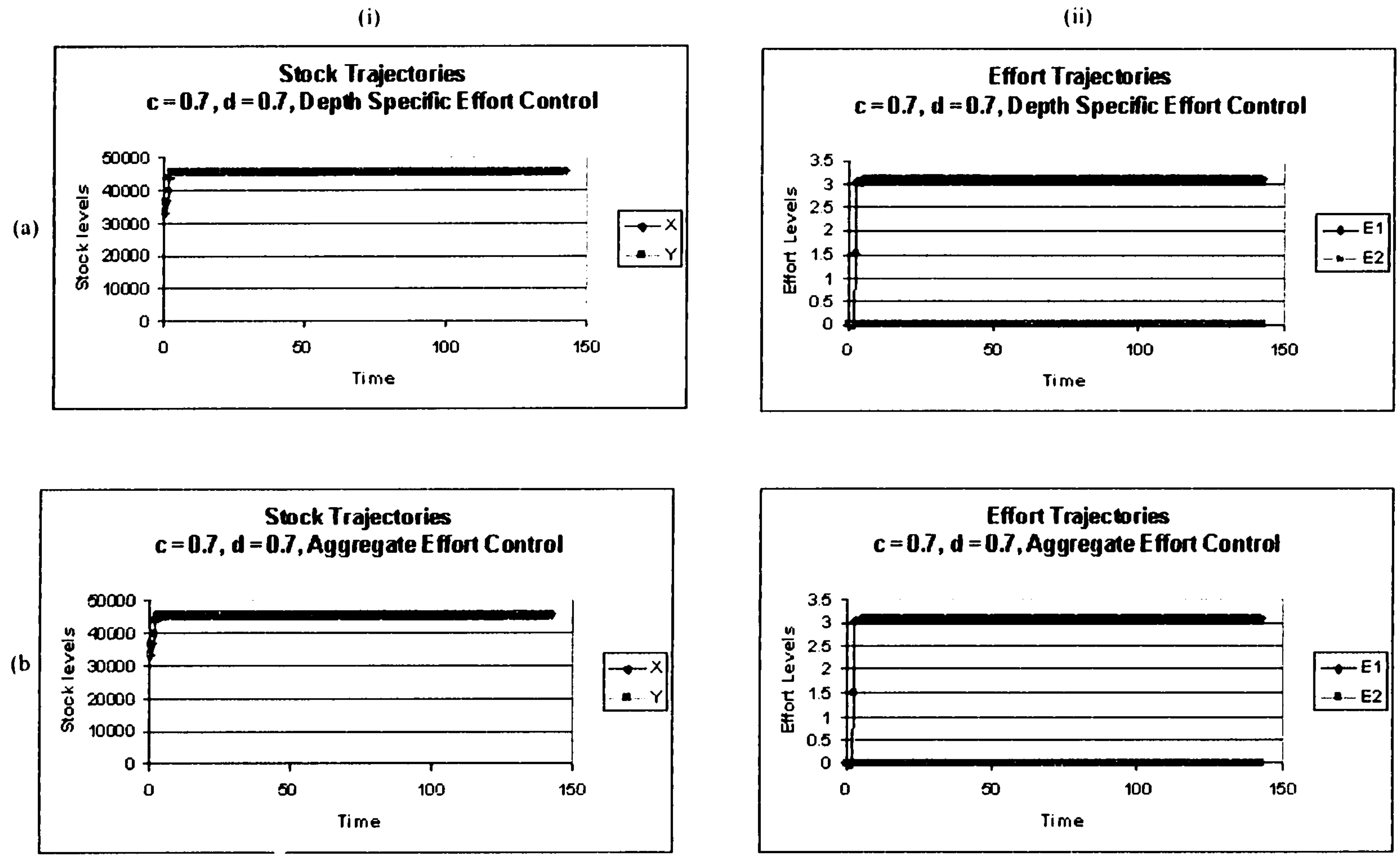

Figure 6. Stock (i) and effort (ii) trajectories for the PDM under depth-specific effort (a) and aggregate effort (b) controls. Stocks in this scenario have an intermediate segregation across depth: 70% of stock *X* is at Depth 1, and 45% of stock *Y* is at Depth 1.

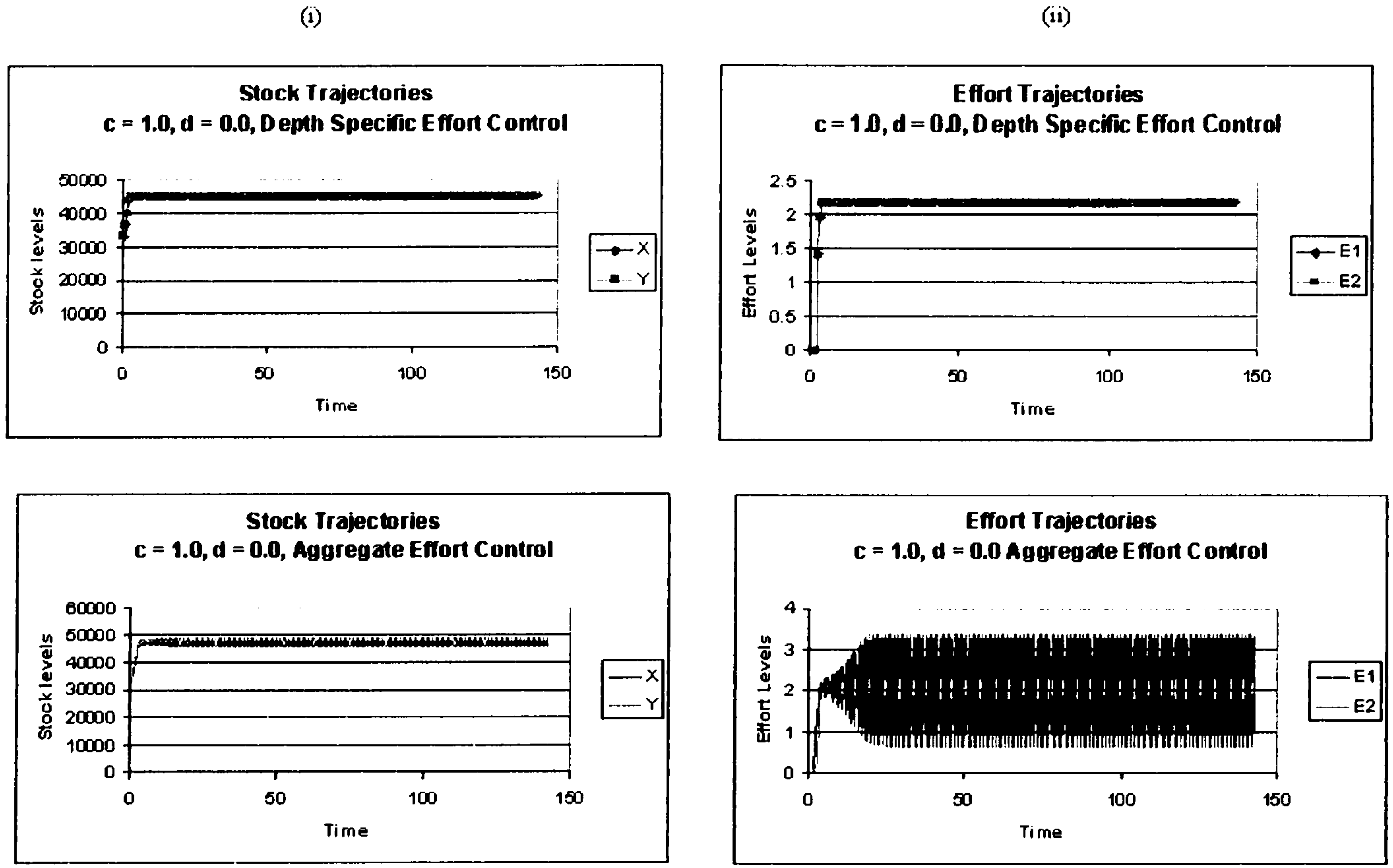

Figure 7. Stock (i) and effort (ii) trajectories for the PDM under depth-specific effort (a) and aggregate effort (b) controls. Stocks in this scenario have extreme segregation across depth: Stock *X* exists only at Depth 1, and Stock *Y* only at Depth 1.

F. Application to the West Coast Trawl Fishery

The West Coast Trawl Fishery (WCTF) is a deepwater bottom trawl fishery off the coast of Central California[18]. The four main species harvested in this fishery are shortspine thornyhead rockfish *Sebastopolus alascanus*, longspine thornyhead *S. altivelis*, Dover sole *Microstomus pacificus*, and sablefish *Anoplopoma fimbria*. Depth recording devices proposed for use in the West Coast Trawl Fishery (WCTF) allow regulators to monitor the time a boat spends trawling at different depths and thus make possible the use of depth-based effort restrictions (Hilborn 1998, p.c.).

Regulators in the WCTF employ a number of regulatory instruments aimed at protecting certain species from overexploitation: Trip limits on shortspine thornyhead strive to reduce fishing pressure on this species; a size minimum on sablefish is intended to prevent harvesters from catching juvenile organisms before they have a chance to reproduce. In fact, both of these regulations lead to high levels of discarding (of dead organisms), seemingly little impact on the harvest of these two species, and resentment on the part of harvesters. Harvest of Dover sole and longspine thornyhead is lucrative; thus fishing pressure remains high despite the regulations. This fishery would benefit from regulations that improve the selectivity of fishing effort *ex ante* rather than attempting to alter behavior through *ex post* "discard requirements." It has been

---

[18] I had the unique opportunity to participate in a three day cruise on an 80-foot vessel in this fleet in December of 1998. I am grateful to Barry and Michael Cohen for this experience.

proposed that depth-based effort rtrictions be implemented as a way of reducing discards and increasing the precision with which regulators can manipulate fishing pressure on individual species (Hilborn 1998, personal communication).

I estimated parameters for two species in the WCTF using data taken from NMFS stock assessment data from 1988 to 1998 and catch data over the period 1964 to 1998. Using maximum likelihood estimation I obtained intrinsic growth rates of 0.160 and 0.114, and carrying capacities of 216×10^3 and 67×10^3 tons for sablefish and shortspine thornyhead respectively.

Depth distributions were obtained from Jacobson (1997) in the form of length-specific depth distributions across depth. Since the PDM assumes a homogeneous size composition, I aggregated biomass across length classes using empirically estimated length compositions and relationships between length and biomass.

In the WCTF dynamic programming, spatial effort controls yield only a small increase in NPV over a 150 year time horizon. The maximum increase in NPV is 2% across all starting stock levels. This small gain is attributable largely to the similarity in the depth distributions of sablefish and shortspine thornyheads. Running the comparison for the same parameters but a higher degree of spatial segregation ($c = 0.7$, $d = 0.114$) yielded a maximum increase of 13% in NPV.

The comparison of policies in the WCTF was run using only sablefish and shortspine thornyhead. As evident in Figure 5, these two species have relatively well correlated depth distributions. Running the simulation for Dover sole and longspine thornyhead, which have more disparate depth distributions, would likely yield a more significant gain in NPV.

G. Conclusions

In resources that have heterogeneous spatial distributions, harvesters have more leeway to engage in rent-dissipating behavior. Aggregate constraints on harvest are suboptimal because the shadow costs of extracted stock is heterogeneous; it is not possible to compel harvesters to internalize the shadow costs through an instrument that does not account for this heterogeneity. The strategic response of harvesters to aggregate harvest restrictions leads to a suboptimal trajectory of harvests over time[19]. Incorporating spatial detail into regulations can lead to increased control over the composition of species harvested and increased social benefits arising from the resource.

I use a simple model of a natural resource with heterogeneous distribution across space to investigate the benefits of a new type of regulatory instrument. I find that a regulation that takes into account spatial structure can increase net present value over time

[19] My analysis here assumes that all landed biomass is retained. In reality, discarding can also result in a loss of resources, though this is not explicitly modeled in the above discussion. Incorporation of discarding would be an interesting extension to the models presented here.

significantly. It is logical that any instrument that reduces the information deficit of the regulator leads to gains in net present value. The extent of these gains is dependent, however, on biological and economic characteristics of the system as well as the initial level of the stocks; incorporation of space into regulation is not always cost-effective. Spatially structured effort regulations are less likely to justify costs of implementation when the stocks are at either extreme of spatial correlation, or when the rate of discount is high,.

The model I develop is an extension of the existing multispecies models presented by Clark, Mesterton-Gibbons and others. Instead of the single type of non-selective effort used in some of the existing models, I introduce two types of effort which are also nonselective. Novel in my model is the use of the fact that both species in the resource are differentially available to the two types of effort; hence choosing the levels of these two levels provides the regulator with a means of altering catch composition that is not available with only a single effort type.

I apply the concept of a Nash equilibrium to the interaction between regulator and harvesters. While the application of this concept to principal-agent problems is clearly not new, I use a novel approach in imbedding it in a dynamic optimization. The existence of a Nash equilibrium implies that harvesters tend toward a corner solution in their allocation of allowable effort. If no such equilibrium exists then harvesters do not reach a steady-state response to the aggregate effort allowance, but instead oscillate between the two spatial strata. This actually leads to a decrease in the need for regulation of the harvesters' choice of effort allocation, since the end result of this oscillatory behavior is not substantially different from that emerging from depth-specific control.

In the numerical results above, I explore the relationship between biological and economic parameters and the gains from implementing depth-specific regulation. While some substantial gains were found in the scenarios examined, the sample of parameter sets I used was not exhaustive. It is likely that there are other parameter sets for which the gains are larger than those reported here.

I estimated parameters for the West Coast Trawl Fishery (WCTF) and apply the analysis to this resource. For the two species studied in the WCTF, it appears that their distributions across depth are too similar to warrant the implementation of depth-specific effort controls. However, numerical results show that for species with the same biological species as those studied, but which are more segregated spatially, more significant gains could be realized. It would be worth parameterizing the PDM with the other species in this system, which have more highly differentiated depth distributions than shortspine thornyhead and sablefish.

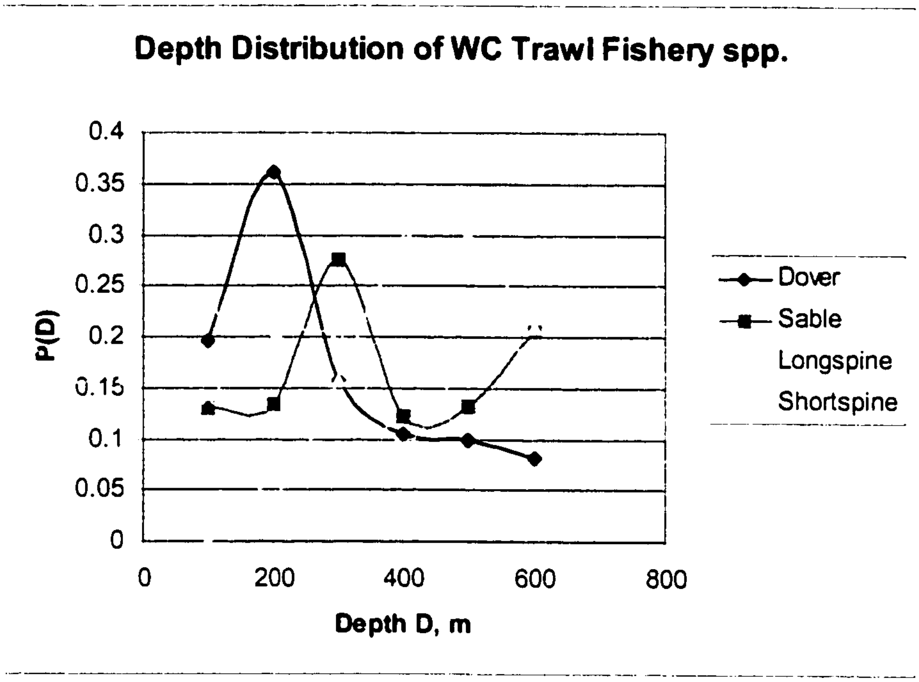

Figure 8. Depth distribution of species in the West Coast Trawl Fishery

The dynamic programming technique used to determine optimal time path of effort can be easily adapted to include stochastic growth or spatial distributions, or spatial distributions of species that follow a density-dependent process. In general the bycatch literature assumes that the species that make up a resource are evenly and deterministically mixed at any point in time; clearly the degree of mixing would be more appropriately modeled as a stochastic variable. The methodology above could be used to determine when this extension to stochastic bycatch rates is likely to make a difference, both for single-pool and spatially structured resources.

Spatially structured multispecies resources provide a new set of theoretical challenges. On one hand they introduce asymmetries of information not present in single-pool resources. They also provide a handle with which a regulator can improve the selectivity of harvest. Informational asymmetry in natural resources can cause significant social losses; the above analysis, working with a fairly simple model of a renewable resource in which these losses arise, provides a methodology for assessing the benefits associated with a technological expansion of the regulator's set of feasible policy instruments.

H. Tables

Table 1. Parameters of the Proportional Depth Model

Parameters	Description (units)
c, d	Proportions at Depth 1 of X and Y respectively (N/A)
r, g	Intrinsic growth rates (N/A)
K, L	Carrying capacities (tons)
q, s	Catchability coefficients (1000s Effort hrs^{-1})
p_x, p_y	Prices (1000s $/ton)
w_1, w_2	Wages of E_1 and E_2 (1000s $/1000 hrs)
δ	Discount rate (N/A)

Table 2. Core Parameter Set for the PDM.

X Parameters	Y Parameters	Other Parameters
c = 0.7	d = 0.3	w_1 = 100
r = 0.4	g = 0.3	w_2 = 100
K = 200	L = 150	δ = 0.05
q = 0.05	s = 0.05	
p_x = 100	p_y = 100	

Table 3. Steady-states of PDM dynamic optimization for various parameters. Other than those noted, parameters are those given in the Core Parameter Set (Table 2).

	Steady-State Stocks and controls					
Parameters	X_{SS}	Y_{SS}	E_1	E_2	λ	θ
Core	100.00	75.8	4.77	2.19	80.00	73.60
$\delta = 0.08$	94.24	70.66	5.02	2.38	78.78	71.70
$c = 0.55$, $d = 0.3$	107.23	67.97	4.48	2.77	70.15	88.23
$w_2 = 150$	100.00	82.07	6.31	1.18	80.00	63.44
$p_x = 20$	104.04	67.97	4.84	2.61	89.24	88.23

Table 4. NPV gains due to spatial regulation, in percentage terms, as a function of various parameter values. Parameters other than those given are the "core set" of Table 2.

Parameters		
c	d	Max %ΔNPV
0.70	0.70	0.0
0.70	0.55	7.2
0.70	0.45	7.7
0.70	0.35	4.3
0.70	0.25	0.5

(a)

Parameters		
r	g	Max %ΔNPV
0.30	0.30	4.8
0.35	0.25	2.4
0.40	0.20	0.9
0.45	0.15	0.5
0.50	0.10	0.0

(b)

Parameter	
δ	Max %ΔNPV
0.000	5.1
0.025	4.9
0.050	4.2
0.075	4.0
0.100	3.2

(c)

Parameters		
p_x	p_y	Max %ΔNPV
1.2	1	7.2
1.4	1	7.6
1.6	1	8.0
1.8	1	8.3
2.0	1	8.5

(d)

PAPER II. STOCHASTIC BYCATCH AND DISCARDING IN A TWO-SPECIES SYSTEM

A. Problem statement and review of literature

Many real-world renewable resources comprise two or more species that have commercial or other value, and spatial correlation of these stocks interacting with nonselective harvest technologies lead to heterogeneous catch compositions. Whether due to "economic, legal, or personal considerations" (Boyce 1996), discarding of organisms is a pervasive phenomenon in fisheries worldwide: Alverson et al. (1994) estimate between 17.9 and 39.5 million metric tons (mmt) of fish are discarded annually, relative to a target catch of 77 mmt. While bycatch is a virtually inevitable consequence of spatial correlation of species, and while some level of discarding is potentially efficient, a significant social loss is associated with both behaviors. Due to the physical trauma of the fishing process, a very small percentage of discarded organisms survive (cf. Alverson et al. 1994, pp. 37ff.).

The problems of bycatch and discarding are largely caused by informational asymmetry between regulators and harvesters. Regulations are necessarily based on retained catch rather than initial harvest; the observational equivalence between discarding and a reduction in initial withdrawals makes the formulation of optimal regulations difficult. A better understanding of the response of harvesters to regulations in different contexts allows for improved construction of (necessarily) second-best regulatory instruments.

A sizeable literature addresses the problem of bycatch and discarding. Alverson et al. (1994) summarize over 800 empirical and theoretical research papers on the topic, and Pascoe (1997) provides a review of numerous economic models. Hall (1996) provides a review of the relevant terminology and attempts to distinguish between bycatch and discarding elicited by market incentives and that brought about by regulatory instruments. There is considerable variation in the definition of "bycatch" across the literature, however, which confounds the discussion about its implications and the analysis of policy.

Most of the economic models of fisheries which allow for discarding abstract away from the dynamic aspect of multispecies fisheries and characterize the single period harvester decisions. A central goal of these studies is to characterize the social inefficiencies associated with discarding and develop regulatory instruments, such as value-based quotas and bycatch requirements, which can potentially mitigate this inefficiency. Single-period models are useful for investigating the short-run discarding decisions of harvesters, but they are deficient for certain purposes; when the rate of discount is low it is erroneous to omit dynamic impacts of bycatch and discarding from models of resource use.

Boyce (1996), for example, considers the relative performance of open-access, season-length limitations, and species-specific transferable quotas, but the analysis is static and the results are independent of the levels of the stocks in question. A number of papers address the impact of tradable quotas (ITQs) on discarding, but the majority of these are static analyses (cf. Arnason 1994; Vestergaard 1996). Turner (1997) analyzes the incentives provided by vessel quotas (i.e. trip limits) for discarding, and suggests that value-based quotas such as those discussed by Turner (1996) and the Icelandic program described by Muse and Schelle (1989).

Very few papers deal with bycatch in a dynamic setting, and virtually none examine the dynamic impacts of discarding. Androkovich and Stollery (1992) present a stochastic, dynamic treatment of bycatch in a two-species system, and compare the effectiveness of pooled taxes, species-specific taxes, and quotas. They find that disaggregated taxes provide the highest dynamic rents, and that price instruments dominate catch quotas. They do not consider discarding, however, or the incentives provided by different regulatory instruments for harvesters to truncate harvest outings prematurely.

The interaction between hold constraints, trip duration and regulatory policy has received little treatment in the literature. Most models which have any representation of stock dynamics treat harvest effort as a pooled, continuous variable, so that there is no way to capture the phenomenon of trip truncation, i.e. termination of a trip before the hold is full. When fishing grounds are far from port, and hence fixed costs associated with each vessel outing are large, trip truncation induced by policy can have an important impact on the average costs of harvest.

Anderson (1999) uses a model of individual vessel behavior, including fixed costs and hold constraints, to show that regulatory instruments such as trip limits and days at sea limitation still allow for harvester to "introduce inefficiencies," i.e. exercise the propensity to dissipate social rents. However, his analysis is static (i.e. the inefficiencies discussed are not viewed in terms of their dynamic effects on stock levels) and he deals with a single-species system.

The goal of this paper is to investigate the performance of regulatory policies vis-à-vis bycatch in a dynamic setting. I use a representation of harvester behavior of sufficiently high resolution to allow for different types of discarding, as well as premature truncation of trips in order to comply with regulations. In addition, I model catch composition as a stochastic process, with each harvester experiencing a different bycatch rate in each period. This notion of stochastic bycatch, unique thus far to Androkovich and Stollery (1992), is a more realistic depiction of the real world than the previous deterministic representations in the literature. Stochasticity and variance in bycatch rates heightens the informational deficit of regulators and makes more evident the moral hazard in the discard decision of harvesters.

B. Model Specification

I consider a system consisting of two stocks, the biomasses of which I denote X and Y. These stocks are exploited by two groups of harvesters, or fisheries, F1 and F2. The system is characterized by a stochastic, unilateral, technological externality (i.e. a stochastic *bycatch* process): With a given unit of harvest effort, harvesters in F1 catch both stock X and stock Y, while F2 catches only stock Y.

This is in part an "individual based," or representative agent, model: Fishing takes the form of *trips*, or vessel outings: In a given time period (fishing season, etc.) there are N_1 and N_2 trips taken by vessels in F1 and F2 respectively. During a trip, each of the vessels exerts effort (e) and withdraws (W) biomass of X, Y, or both. Depending on their incentives, they either retain (R) or discard (D) the biomass they withdraw; naturally it must be the case that $R + D = W$. I assume all discarded stock is lost from the system[20].

The total harvest retained (R_X and R_Y) by a vessel is physically constrained by the vessel's *hold capacity*: Retained hold capacity for vessels in F1 and F2 are denoted $\overline{R_1}$ and $\overline{R_2}$ respectively. Note that effort (e) is not constant across vessel trips; vessels which discard part of their withdrawals – unless they truncate their trip before filling their hold – exert more effort than those vessels which retain all their withdrawals.

This system is assumed to have excess capacity of vessels under open-access, leading to rent dissipation in the absence of regulation. To counteract this tendency, the system is governed by a benevolent central planner, or "regulator," who strives to maximize

---

[20] It is reasonable to assume that discards are "removed" from the system, given the high rate of mortality of discarded organisms in most cases. In some fisheries, survival rates are significant; this survival could be incorporated into the model.

dynamic discounted rents. As discussed below, the regulator is able to manipulate N_1 and N_2, but *not* the effort levels (e's) *per se* exerted by individual vessels). In addition, the regulator can impose a constraint on the retention of stock Y by F1, i.e. a "bycatch constraint." The bycatch constraint at time t, whatever form it takes, is represented in the discussion below by the parameter τ_t.

1. Biology (stock dynamics)

Stocks in this system evolve according to the standard logistic form pervasive in the literature. I use a discrete-time formulation, as this is more compatible with discrete vessel outings within a time period as I discuss below. Equations of motion for the two stocks are given by

$$
\begin{aligned}
X_{t+1} &= X_t + r_X X_t\left(1-\frac{X_t}{K_X}\right) - W_{Xt} \\
Y_{t+1} &= Y_t + r_Y Y_t\left(1-\frac{Y_t}{K_Y}\right) - W_{Yt}
\end{aligned}
\qquad (25)
$$

where r_X and r_Y are the intrinsic (maximum per-capita) growth rates, and K_X and K_Y are the carrying capacities, of X and Y respectively. As discussed above, W_{Xt} and W_{Yt} are the amounts of X and Y biomass removed from the system during period t, including both retained and discarded biomass.

The growth equations (25) imply that reproduction takes place at the beginning of the harvest season, i.e. before any withdrawals have been made. However, since withdrawals at time t depend upon stock levels at time t, the implication is that the biomass produced at time t is not recruited to the fishery until *after* time t harvest takes place.

2. Production functions

For a given level of effort, e_{1jt}, by a certain vessel j in F1 at time t, the harvest functions (i.e. total stock withdrawn from the system) are the standard Schaefer type, given by

$$(26) \quad \begin{aligned} W_{1Xjt} &= q_{1X} e_{1jt} X_t \\ W_{1Yjt} &= \theta_{1j} q_{1Y} e_{1t} Y \end{aligned}$$

Here q_{1X} and q_{1Y} are the baseline catchability coefficients of stocks X and Y with respect to effort by F1 vessels. Catchability of Y by F1 is determined in part by θ_{1jt}, the time t realization of a vessel-specific random variable with mean unity and variance $\sigma^2_{\theta_1}$; each vessel in F1 catches Y at a different rate, given particular biomass levels of X and Y. To be more precise, the catchability of Y by F1 vessels is a random variable, $Q_{1jYt} = q_{1Y}\theta_{1jt}$, with mean q_{1Y} and variance $\sigma^2_{\theta_1}$. In the discussion below, I refer to q_{1Y} as the "mean catchability" of Y by F1.

Total withdrawals by F1 at time t are obtained by summing (26) over all vessels in F1:

$$(27)\quad \begin{aligned} W_{1Xt} &= \sum_{j=1}^{N_{1t}} q_{1X} e_{1jt} X_t \\ W_{1Yt} &= \sum_{j=1}^{N_{1t}} \theta_{1jt} q_{1Y} e_{1jt} Y_t \end{aligned}$$

Vessels in F2 catch only Y; in the notation used above, I assume $q_{2X} = 0$.[21] Withdrawal functions for effort e_{2kt} exerted by vessel k at time t are given by

$$(28)\quad \begin{aligned} W_{2Xkt} &= \theta_{2jt} q_{2X} e_{2kt} X_t = 0 \\ W_{2Ykt} &= q_{2Y} e_{2kt} Y_t \end{aligned}$$

and total withdrawals by F2 at time t are

$$(29)\quad \begin{aligned} W_{2Xt} &= \sum_{k=1}^{N_{2t}} \theta_{2kt} q_{2X} e_{2kt} X_t = 0 \\ W_{2Yt} &= \sum_{k=1}^{N_{2t}} q_{2Y} e_{2kt} Y_t \end{aligned}$$

Total withdrawals of X and Y in a given time period are therefore given by

$$(30)\quad \begin{aligned} W_{Xt} &= W_{1Xt} + W_{2Xt} \\ W_{Yt} &= W_{1Yt} + W_{2Yt} \end{aligned}$$

---

[21] The unilateral nature of the bycatch externality could be relaxed by allowing $q_{2X} > 0$. The bycatch of X by F2 would then also be a stochastic process, based on the parameter θ_{2jt} with mean unity and variance $\sigma^2_{\theta_2}$.

3. *Economic variables*

Output from both fisheries is sold in competitive markets; all vessels are price takers. F1 sells retained *X* at a constant price p_X and F2 sells retained *Y* at a price p_Y. F1, however, has a *comparative disadvantage* in the processing or marketing of *Y* and therefore sells it at a discounted price $(1-\gamma)p_Y$, where γ is an industry-specific parameter such that $0 \le \gamma \le 1$. I refer to γ as the "coefficient of inefficiency" for F1 vessels harvesting *Y*.

For example, suppose *X* is Pollock and *Y* is Halibut. F1 is a high-seas trawler fishery for Pollock in which vessels flash freeze all their catch, including bycaught halibut. F2 is a longline halibut fishery that catches only Halibut, and sells it fresh. While the catchability coefficients q_{1Y} and q_{2Y} capture the respective availability of Halibut to the trawl and the longline respectively, γ captures the fraction of the value of Halibut lost due to freezing.

In the discussion below I assume that $p_Y > p_X$; however, it is interesting to consider both the case where $(1-\gamma)p_Y > p_X$, in which case F1 vessels have an incentive to highgrade, and the case where $(1-\gamma)p_Y < p_X$, whereupon F1 vessels might discard *Y* in order to harvest more *X*. Regulatory policy can alter the perceived ex-vessel benefits of harvesting X and Y, e.g. a per-unit tax on *Y* makes discards of *X* in favor of *Y* less likely and discarding of Y more likely. I discuss in detail below the conditions under which the two types of discarding arise.

Total revenue during period t for a given vessel in F1 is given by

$$(31) \qquad TR_{1jt} = p_X R_{1Xjt} + (1-\gamma) p_Y R_{1Yjt}$$

and the total revenue accruing to F1 as a whole is

$$(32) \qquad TR_{1t} = \sum_{j=1}^{N_1} \left[p_X R_{1Xjt} + (1-\gamma) p_Y R_{1Yjt} \right]$$

Similarly, per-vessel and total revenues accruing to F2 are given by

$$(33) \qquad \begin{aligned} TR_{2kt} &= p_X R_{2Xkt} + p_Y R_{2Ykt} = p_Y R_{2Ykt} \\ TR_{2t} &= \sum_{k=1}^{N_2} \left[p_Y R_{2Ykt} \right] \end{aligned}$$

Vessels incur fixed costs of FC_1 and FC_2 in F1 and F2 respectively. These cost incur such things as steaming to fishing grounds, preparing gear, etc. Naturally these fixed costs affect only the entry/exit decision of a vessel, i.e. whether or not to fish, but do not affect effort levels within a trip, discarding decisions, or the incentive to truncate a trip before the hold is full.

Marginal cost of effort is constant for both of the fisheries, so total costs in F1 and F2 are linear in the total amount of effort exerted:

$$(34)\quad \begin{aligned} TC_{1t} &= N_1 FC_1 + \sum_{j=1}^{N_1} c_1 e_{1jt} \\ TC_{2t} &= N_2 FC_2 + \sum_{k=1}^{N_2} c_2 e_{2kt} \end{aligned}$$

The marginal cost to F1 vessel j of harvesting X and Y are given respectively by

$$(35)\quad \begin{aligned} MC_{1jXt} &= \frac{c_1}{q_{1X} \cdot X_t} \\ MC_{1jYt} &= \frac{c_1}{\theta_{1jt} q_{1Y} \cdot Y_t} \end{aligned}$$

C. Regulation and harvester response

I assume that the regulator uses two classes of regulatory instruments to achieve the maximization of dynamic social rents: (i) a constraint on inputs, in the form of a restriction on the number of vessel trips taken in each of the fisheries (N_1 and N_2 in F1 and F2 respectively), and (ii) a constraint on the retained catch of Y by F1. Note that regulation (ii) necessarily focuses on the *retained* catch. It cannot directly address either discarding *per se* or total withdrawals, as neither of these are observable. I represent the bycatch constraint at time t with the parameter τ_t, which can take the form of – among other possibilities not explored in detail – a trip limit (maximum retention of Y per F1 vessel trip), a limit on the value of the vessel's hold contents, or a tax on bycatch.

I assume the regulator knows the biomass levels X_t and Y_t at time t with certainty. However, the regulator has imperfect information about the composition of the catch

W_{1jt} withdrawn from the system by F1 vessel j; all information about catch per unit effort (CPUE) is embodied in the (known) distribution of the random bycatch parameter θ_{1jt} and its interaction with the biomass levels. Due to the informational asymmetry, harvesters can extract short-run informational rents, and the social benefits achieved under regulation are inherently second-best.

In response to the state of nature and bycatch regulations (if any), harvesters choose from a number of options. If maximized rents exceed the fixed costs they must pay to operate, they can (i) simply fill their hold with the natural catch composition; (ii) truncate their trip, returning to port with a partially filled hold; (iii) discard X in order to fit more Y into their hold; or (iv) discard Y in order to take on more X. Note that the actual level of fishing effort e_{jt} exerted by a harvester j at time t depends on which of these options is chosen: Trip truncation requires less effort than filling the hold, and both of the discarding options require more effort than is initially needed to fill the hold. The effort level e_{1jt} is not directly observable by the regulators (as it is in most bioeconomic models), so that effort *per se* cannot be used as a control variable.

The choice of behavior arises from the interaction between the biological and technological parameters of the system (i.e. biomass levels and catchability coefficients, as well as the realization of the random bycatch parameter θ_{1jt}), the economic parameters (e.g. wages, fixed costs, prices p_X and p_Y, as well as the "comparative disadvantage" parameter γ), and the regulatory parameter τ. The regulator solves the social optimization problem contingent upon the aggregate harvester response functions, which for F1 are of the general form

$$
\begin{aligned}
e_{1Xt} &= \sum_{j=1}^{N_1} e_{1jXt}\left(X_t, Y_t, \theta_{1jt}, p_X, p_Y, \gamma, \tau_t\right) \\
D_{1Xt} &= \sum_{j=1}^{N_1} D_{1jXt}(\cdot) \\
D_{1Yt} &= \sum_{j=1}^{N_1} D_{1jYt}(\cdot) \qquad (36) \\
R_{1Xt} &= \sum_{j=1}^{N_1} R_{1jXt}(\cdot) \\
R_{1Yt} &= \sum_{j=1}^{N_1} R_{1jYt}(\cdot)
\end{aligned}
$$

For any given vessel j, retention of X and Y is constrained by the hold capacity of the vessel:

$$R_{1jXt} + R_{1jYt} \le \overline{R_1} \qquad \forall j = 1 \ldots N_1$$

Behavior of vessels in F2 is simpler, and is independent of all variables other than the biomass of Y and its catchability coefficient:

$$
\begin{aligned}
e_{2t} &= N_2 \frac{\overline{R_2}}{q_{2Y} Y} \\
D_{2Xt} &= D_{2Yt} = 0 \qquad (37) \\
R_{2Xt} &= 0 \\
R_{2Yt} &= N_2 \overline{R_2}
\end{aligned}
$$

While it is true that, *ceteris paribus*, the regulator would prefer to have a given unit of *Y* captured by F2 rather than F1, it is virtually never optimal to prohibit retention of *Y* by F1. Bycatch of *Y* is an exogenously determined consequence of the harvest of *X*, so such a prohibition would either lead to F1 closing down altogether or to high levels of discarding of *Y* by F1. The regulator seeks an internal optimum in the harvest and retention of *Y* by F1 (i.e. a tradeoff between excessive bycatch and excessive discarding), while at the same time eliciting the best possible *aggregate* dynamic harvest of *X* and *Y* by F1 and F2 combined.

In the following section, I derive the conditions under which harvesters choose a behavior from (i)-(iv) described above, i.e. trip completion (full hold) with no discards, trip truncation (partially filled hold) with no discards, trip completion with discarding of *X* for *Y*, and trip completion with discarding of *Y* for *X*.

1. Harvester response to regulations

Constrained by their hold capacity and any regulatory instrument used to control bycatch, each F1 harvester solves a static[22] optimization (profit-maximization) problem with respect to their three available choice variables: Harvest effort (e_{1it}), discards of *X*

---

[22] The static nature of the harvesters' perspective emerges from the open-access assumption: If there are many harvesters, then each takes stock levels and other system parameters as exogenous in any time period. They do not have an incentive to internalize their dynamic impact on stock levels or on the regulations imposed upon the fishery.

$\left(D_{1jXt}\right)$, and discards of Y $\left(D_{1jYt}\right)$. I assume harvesters know the realization of the bycatch parameter (or "state of nature") θ_{1jt} *ex ante*. I further assume that stock levels and prices are deterministic and known at the time behavior is chosen by the harvester. The harvester's optimization problem consists of a linear objective function and linear constraints, and so is straightforward to solve analytically.

I consider harvester response to four potential regulatory scenarios: No constraint on bycatch (henceforth denoted NC); price control (per-unit tax/subsidy) on bycatch (TX); a trip limit (TL), or vessel quota, on bycatch biomass; and a value-based vessel quota (VL), i.e. a limit placed on the market value of biomass (both X and Y) retained by F1 vessels. The harvesters' profit maximization problems are given below, and behavioral responses to these four types of regulation are summarized in

Table 10. The solution to the harvester's optimization problem under a price instrument is described in more detail in Appendix 1.

a) Regulatory scenario NC: Unconstrained bycatch

I first describe the scenario where the regulator controls only aggregate effort levels in F1 and F2 (in the form of number of vessel outings N_1 and N_2), with no constraint specifically placed on the level of bycatch R_{1jYt} retained by individual F1 vessels. Under these regulatory conditions, the harvester solves the following constrained profit-maximization problem:

$$(38) \qquad \max_{e_{1jt}, D_{1jXt}, D_{1jYt}} p_X(q_{1X}e_{1jt}X_t - D_{1jXt}) + (1-\gamma)\, p_Y\left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) - c_1 e_{1jt} - FC_1$$

subject to the non-negativity constraints (on, respectively, effort, discards of X and Y, retained catch of X and Y):

$$e_{1jt} \geq 0$$
$$D_{1jXt} \geq 0$$
$$D_{1jYt} \geq 0$$
$$q_{1X}e_{1jt}X_t - D_{1jXt} \geq 0$$
$$\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt} \geq 0$$

and a hold constraint

$$\overline{R_1} - \left(q_{1X}e_{1jt}X_t - D_{1jXt}\right) - \left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) \geq 0 .$$

The solution to this problem for different combinations of stock levels and relative prices is given in Table 7, for those vessels that choose to operate. Note that if a vessel's maximized value of (38) is negative, they choose not to produce at all.

If the disparity between prices (taking into account the coefficient of comparative disadvantage γ) is large enough in either direction to offset marginal costs of procuring additional units of the more valuable stock, discarding takes place. Given the linearity of the objective function and harvest costs, discarding – if it takes place at all for a given realization of θ_{1it} – continues until the entire hold is full of the preferred stock.

Figure 9 shows the behavior of a representative harvester in extensive game form, i.e. as a decision tree, when catch composition is unregulated. Once nature (N) determines the bycatch parameter θ_{1it}, the harvester chooses one of three actions: Fill the hold with the natural catch composition, selectively retain only Y and fill the hold with all Y, or fill the hold with only X. Since no disincentive for retaining bycatch is used in this case, the latter behavior is only chosen if $(1-\gamma)p_Y < p_X$, i.e. if $\gamma > 1 - p_X / p_Y$.

b) Regulatory scenario TX: Price instrument(tax/subsidy) on bycatch

Now, suppose the regulator utilizes a price instrument τ_t to alter harvesters' incentives vis-à-vis bycatch. I assume τ_t to be a per-unit tax (or, if negative, a subsidy) applied to retained bycatch R_{1iYt}. In this case, the harvester faces the following problem:

$$\max_{e_{1jt}, D_{1jXt}, D_{1jYt}} p_X(q_{1X}e_{1jt}X_t - D_{1jXt}) + \left[(1-\gamma)p_Y - \tau_t\right]\left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) - c_1 e_{1jt} - FC_1$$

subject to the non-negativity constraints (on, respectively, effort, discards of X and Y, retained catch of X and Y:

$$\begin{aligned}
&e_{1jt} \geq 0 \\
&D_{1jXt} \geq 0 \\
&D_{1jYt} \geq 0 \\
&q_{1X}e_{1jt}X_t - D_{1jXt} \geq 0 \\
&\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt} \geq 0
\end{aligned}$$

and a hold constraint.

The solution to this problem is given in Table 8. The choice of behavior category depends as indicated on certain critical values of τ_t, with these critical values dependent on the stock levels, economic variables, and the realization of the stochastic bycatch

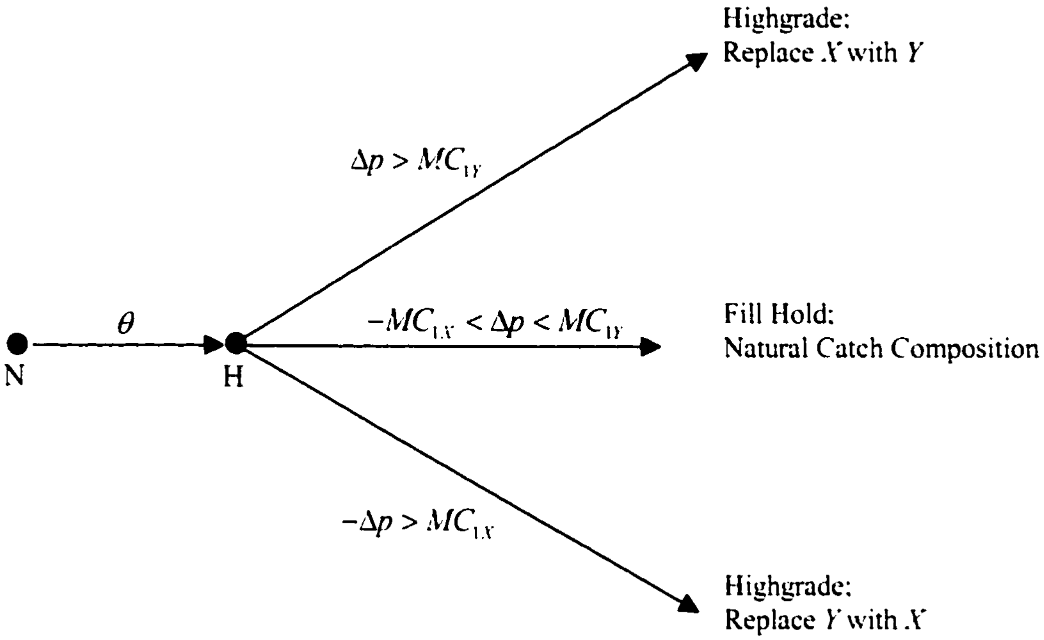

Figure 9: Harvester behavior in the absence of an explicit bycatch control

parameter. The vessel chooses to shut down altogether if the marginal benefit of effort, net of the tax, is negative. That is, it shuts down if the tax exceeds a critical level $\overline{\tau_t}$, where

(39) $$\overline{\tau_t}(X_t, Y_t) = \left[p_{1X} q_{1X} X_t + (1-\gamma) p_Y \theta_{1jt} q_{1Y} Y_t - c_1 \right] / q_{1Y} Y_t .$$

If the tax is less than $\overline{\tau_t}$ but greater than

(40) $$\tau_t^Y (X_t, Y_t) = c_1 / q_{1X} X_t - p_X + (1-\gamma) p_Y ,$$

the vessel finds retention of Y unprofitable and discards Y in favor of X. If the tax is *low* enough, i.e. less than

(41) $$\tau_t^X (X_t, Y_t) = (1-\gamma) p_Y - p_X - \frac{c_1}{\theta_{1jt} q_{1Y} Y_t}$$

then the harvester discards X in favor of Y. For positive values of the price differential $(1-\gamma) p_Y - p_X$, a subsidy ($\tau_t < 0$) is required to elicit discarding of Y (though it was never optimal to employ such a policy in the scenarios I investigated).

While the criteria for the choice between behaviors differ from those in the NC scenario (no bycatch constraint), the resulting choice variables for each behavior category are the same as in the unconstrained case. Due to the linearity of the harvester's objective function, truncation of a trip prior to filling the hold is never desirable.

Note that since

$$(42) \qquad \tau_t^Y - \tau_t^X = \frac{c_1}{q_{1X}X_t} + \frac{c_1}{\theta_{1jt}q_{1Y}Y_t} > 0,$$

there are no values of τ_t such that both types of discarding result. Importantly, as long as wages are positive, it is *always* possible to choose a price instrument such that no discarding takes place. Figure 10 shows the extensive game form of the bycatch tax scenario, and indicates that the regulator can choose a level of the tax such that no highgrading takes place, *regardless* of the realization of the bycatch parameter. This non-intersection of the two discarding regions is also illustrated in Figure 11, which shows the behaviors resulting from different values of the bycatch tax.

c) Regulatory scenario TL: Trip limit (vessel quota) on bycatch of *Y*

Now suppose the regulator controls retention of *Y* via a vessel quota, or trip limit, on the retention of *Y*. I assume full compliance with the letter of this regulation if not necessarily the spirit (which is, ostensibly, to reduce highgrading in favor of *Y*). If the harvester experiences low levels of bycatch – due either to a low stock of *Y* or to a low realization of θ -- it may be in his best interest to continue harvesting and replace the *X* in their hold with newly caught *Y* to take full advantage of the bycatch allowance.

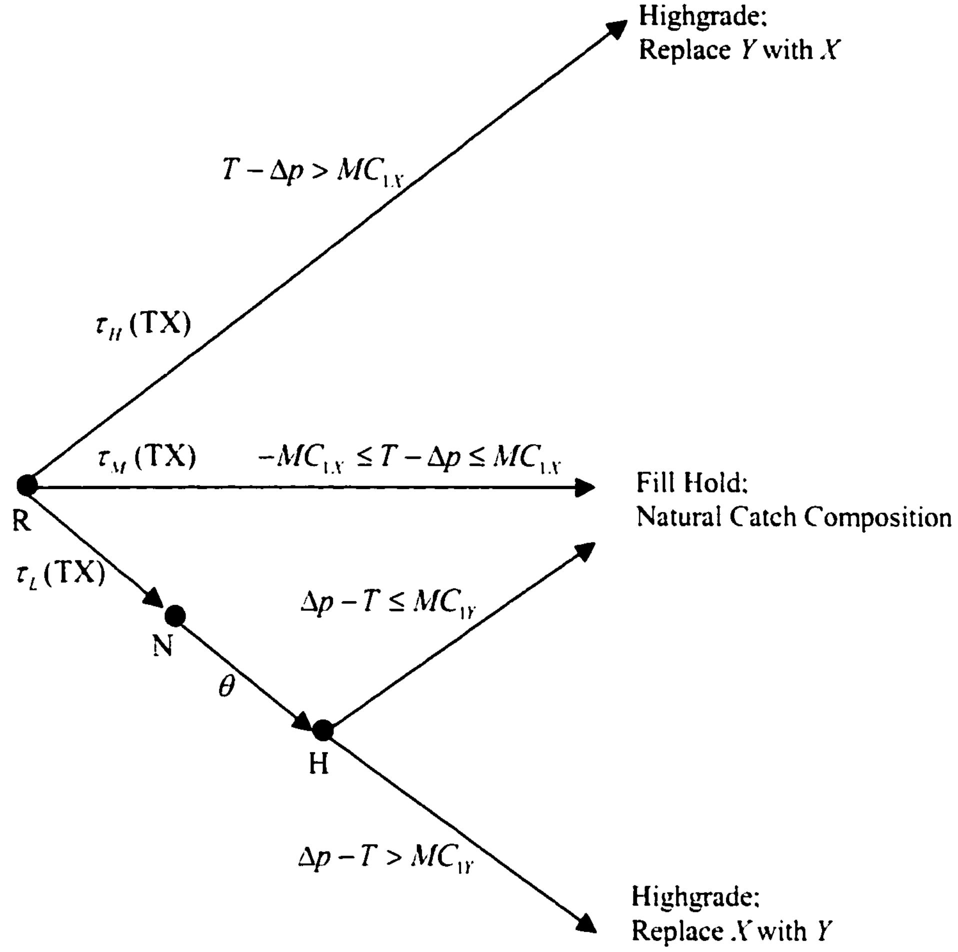

Figure 10: Harvester behavior in response to a tax on retained bycatch of *Y*.

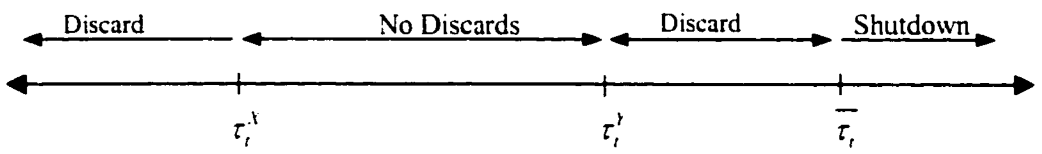

Figure 11: Ranges of the bycatch tax τ_t corresponding to different harvester behavior for fixed values of all other variables.

Alternatively, if the trip limit constrains their retention of Y below the natural amount occurring in a full hold, he may fill the remainder of their hold with X. As he does this, he withdraws Y along with the additional X; that Y is discarded and lost to the system.

The harvester's problem in the face of a bycatch trip limit is

$$\max_{e_{1jt}, D_{1jXt}, D_{1jYt}} p_X(q_{1X}e_{1jt}X_t - D_{1jXt}) + (1-\gamma)\, p_Y\left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) - c_1 e_{1jt} - FC_1 .$$

subject to the non-negativity constraints:

$$\begin{aligned}
&e_{1jt} \geq 0; \\
&D_{1jXt} \geq 0; \\
&D_{1jYt} \geq 0; \\
&q_{1X}e_{1jt}X_t - D_{1jXt} \geq 0; \\
&\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt} \geq 0,
\end{aligned}$$

the hold constraint

$$\overline{R_1} - \left(q_{1X}e_{1jt}X_t - D_{1jXt}\right) - \left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) \geq 0$$

and now, in addition, the trip limit constraint

$$\tau_t - \left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) \geq 0 .$$

Depending on the size of the trip limit τ_t, it may or may not be binding when the hold is initially filled with the naturally occurring catch composition. The trip limit binds if

(43) $$\tau_t < \overline{R_1}\left(\frac{q_{1Y}Y_t}{\theta_{1jt}q_{1Y}Y_t + q_{1X}X_t}\right).$$

If the trip limit binds before the hold capacity is reached, the harvester can either truncate the trip and return to port with a partially filled hold or, if it is profitable to do so, she can continue to exert effort, retaining only *X* and discarding any *Y* she withdraws. It is profitable to continue and selectively retain *X* if the price of *X* exceeds its marginal cost, i.e. if $p_X \geq MC_{1X} = c_1/q_{1X}X_t$.

If the trip limit does not bind, the harvester can return to port with a full hold containing less than the allowed amount of *Y*. However, if the benefits of retained *Y* are sufficiently greater than those of *X*, the harvester may choose to highgrade, i.e. continue to harvest, selectively retaining *Y* and using it to replace the *X* already in the hold. Highgrading is only profitable, however, if the price of *Y* to the F1 vessel is great enough to offset both the marginal cost of obtaining it as well as the opportunity cost of the displaced *X*, i.e. if

(44) $$(1-\gamma)p_Y - p_X > MC_{1Y}$$

If the vessel chooses to highgrade, *X* is discarded for two reasons: As unwanted catch arising from the highgrading effort, and as catch displaced from the hold by the newly acquired *Y*.

Table 9 summarizes the choice variables associated with different levels of the bycatch trip limit; the Appendix gives a solution to the constrained maximization problem. Figure 12 shows the extensive game form of the Trip Limit Scenario.

The potential behavior of a harvester is illustrated in *X*-*Y* space in Figure 13. The hold constraint requires the harvester to be on or inside the line *HC*. For low values of θ (i.e. $\theta = \theta_L$), the harvester moves along the vector θ_L until the hold constraint binds at point C. At this point, the harvester is still allowed some more *Y*; $Y_C < \tau_{TL}$, so she is inside the trip limit constraint. If it is profitable, she moves along the hold constraint from C to B, discarding *X* in the amount of $D'_X + D''_X$. D'_X is the amount of *X* discarded from the hold, i.e. displaced by the newly caught *Y*; D''_X is the *X* harvested with the additional *Y* and subsequently discarded. If highgrading in favor of *Y* is not profitable, the harvester remains at point C, and returns to port with a hold full of the natural catch composition.

For a high value of $\theta = \theta_H$, the trip limit binds before the value limit, at A. In this case, the harvester has two options, the choice of which depends upon the profitability of retaining only *X*: If harvest effort is only profitable on the margin if both *X* and *Y* are retained, he truncates his trip with the catch represented by A. If he does this, his hold is not full: An amount R^-_{TL} of hold capacity goes unused. Alternatively, the harvester can choose to continue harvesting, selectively retaining only *X*. Thus he moves *along* the trip limit constraint to point B. In so doing, he catches and discards Y in the amount of D_Y.

Note that the slope of the catch trajectories is determined not only by the realization of θ, but by the stock levels and catchabilities as well. For example, when $\theta = \theta_H$, the slope of the stock trajectory is

$$m = \theta_H \frac{q_Y Y}{q_X X}.$$

There is some $\theta = \bar{\theta}$ such that the catch trajectory passes through the hold constraint and trip limit at their point of intersection. There is no incentive for the harvester to discard either stock or halt their trip prematurely. In a sense, this is the regulatory grail: All stock caught is retained, and there is no inefficient use of capital (and hence elevated average costs) in the form of partially empty holds.

d) Regulatory scenario VL: Value limit on hold contents

I now suppose the regulator imposes a value-based quota on catch retained by vessel j. This type of quota has been used with success to reduce highgrading in multispecies and multigrade resources [Muse, 1989 #150], and their theory has been explored in a static setting [Turner, 1996 #149; Vestergaard, 1996 #132]. I assume full compliance with the value limit. The impact of this policy is qualitatively similar to that of the trip limit (or biomass-based quota) discussed in Regulatory Scenario TL: The harvester may or may not fill the hold before the limit is reached. If the limit does not bind, they may continue to exert effort, discarding less valuable biomass (X) and replacing it with the more valuable Y. Thus two types of discards of X arise as in the bycatch trip limit.

An important distinction between the physical trip limit and the value-based limit is that if the limit *is* binding (i.e. the value maximum is reached before the hold is filled), there is no incentive to continue harvesting. That is, binding value limits always lead to trip truncation and never to selective retention of the target stock (X)

The harvester's profit maximization problem when faced with a value limit is

$$\max_{e_{1jt}, D_{1jXt}, D_{1jYt}} p_X(q_{1X}e_{1jt}X_t - D_{1jXt}) + (1-\gamma)\, p_Y\left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) - c_1 e_{1jt} - FC_1$$

subject to the non-negativity constraints:

$$\begin{aligned} &e_{1jt} \geq 0 \\ &D_{1jXt} \geq 0 \\ &D_{1jYt} \geq 0 \\ &q_{1X}e_{1jt}X_t - D_{1jXt} \geq 0 \\ &\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt} \geq 0 \end{aligned},$$

the hold constraint

$$\overline{R_1} - \left(q_{1X}e_{1jt}X_t - D_{1jXt}\right) - \left(\theta_{1jt}q_{1Y}e_{1jt}Y_t - D_{1jYt}\right) \geq 0,$$

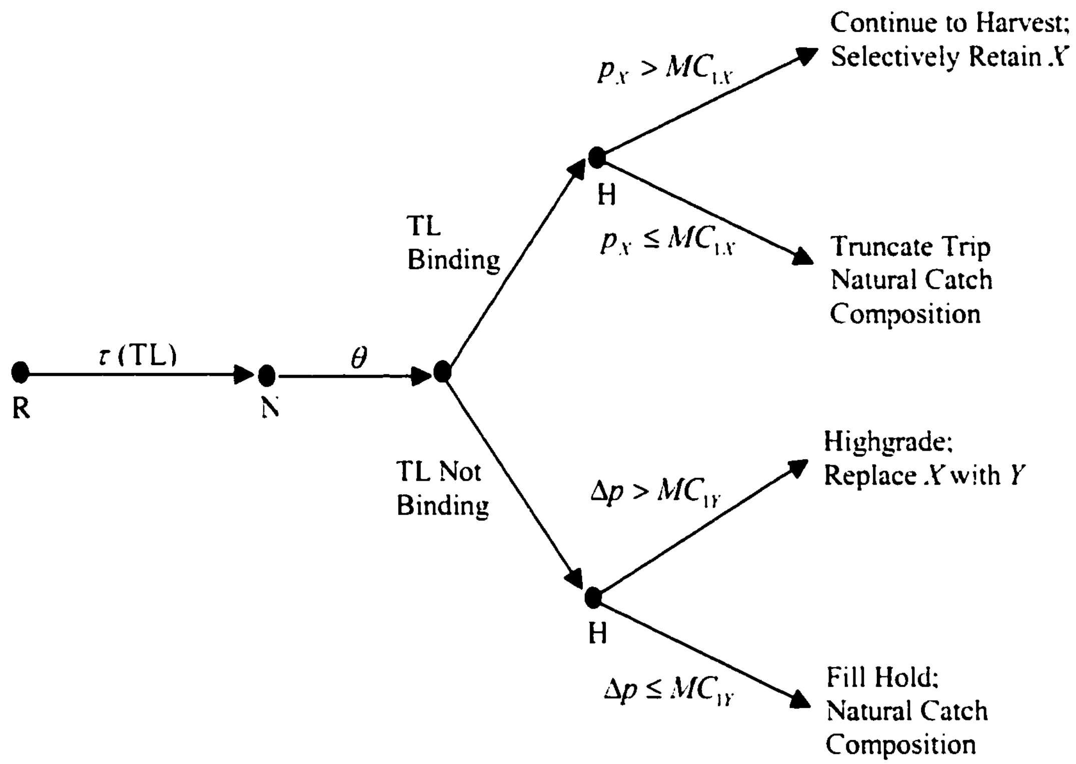

Figure 12: Decision tree for harvester behavior under a trip limit on retained bycatch of *Y* by F1 vessels.

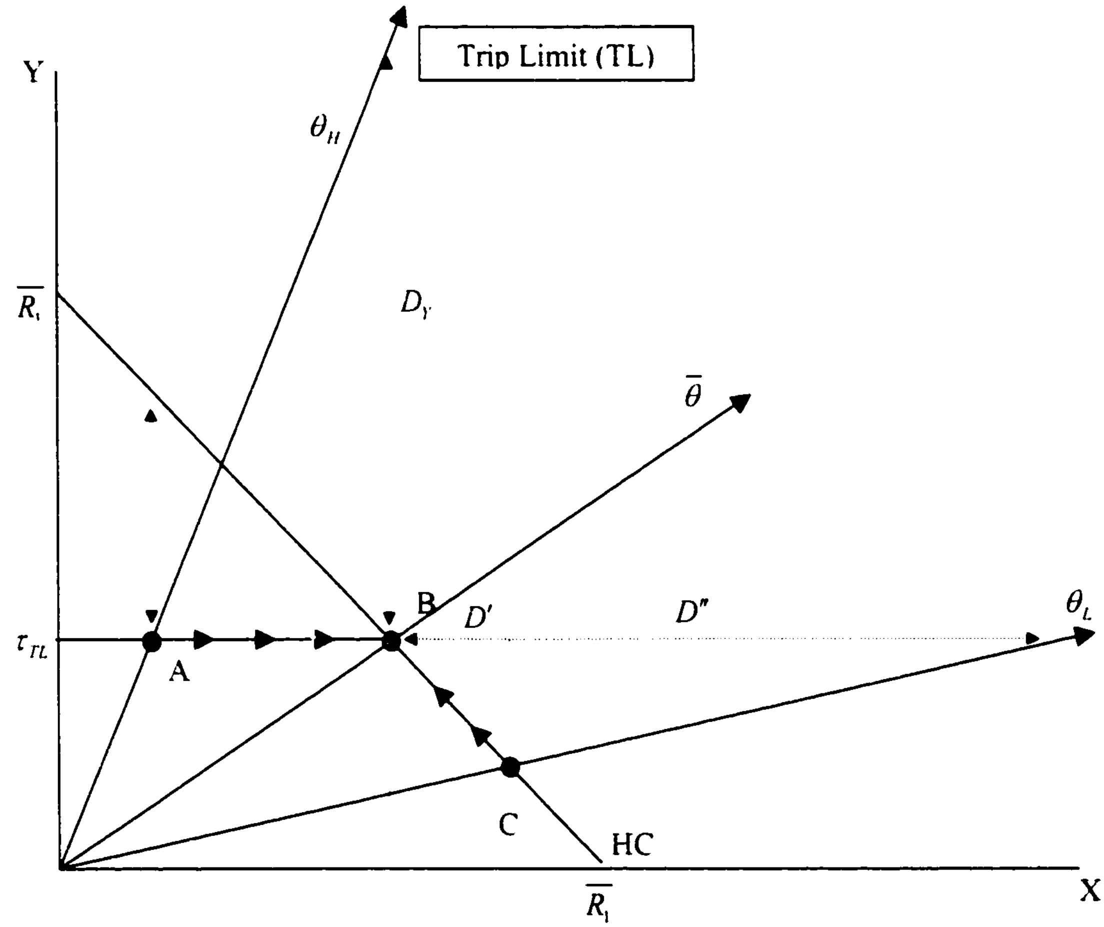

Figure 13: Potential harvester behavior in X-Y space in the presence of a trip limit τ_{TL} on retained *Y*

and the catch value constraint

$$\tau_t - \left[p_X R_{1jXt} + (1-\gamma) p_Y R_{1jYt} \right] \geq 0 .$$

The value limit is binding only if the value of a hold filled with the naturally occurring catch composition exceeds the limit τ_t, i.e. if

$$(45) \qquad \overline{R_1} \left[\frac{p_X q_{1X} X_t + (1-\gamma) p_Y \theta_{1jt} q_{1Y} Y_t}{q_{1X} X_t + \theta_{1jt} q_{1Y} Y} \right] > \tau_t$$

If this condition holds, the harvester truncates the trip with a partially filled hold. If the limit is not binding, the harvester highgrades (discards X in favor of new, selectively retained Y) until the allowed value limit is reached, but only if it is profitable to do so. The condition for profitability of this highgrading behavior is as given in (44) above.

Figure 14 shows the extensive game form for the Value Limit case. Note the similarity to Figure 12 (Trip Limit case), except for the absence of selective retention of X once the limit binds.

The behavior of harvesters under the VL scenario is illustrated in an alternative form in Figure 15. When $\theta = \theta_L$, the situation is similar to that for the trip limit depicted in

Figure 13: The hold constraint binds before the regulatory constraint, at point C. If profitable the harvester highgrades in favor of Y, moving along the regulatory frontier to B. In the process, they discard $D' + D''$, as in the trip limit case.

As in the TL case, when $\theta = \bar{\theta}$, the regulatory constraint and the hold constraint bind at the same time. There is no incentive for the harvester to discard either stock or halt their trip prematurely.

When $\theta = \theta_H$, the regulatory constraint binds at A. However, in this case there is no incentive for any discarding behavior such as the selective retention of X exhibited in the TL case. The harvester truncates the trip at A, leaving R_{VL}^- of hold capacity unused.

The TL and VL scenarios depicted in Figure 13 and Figure 15 are worthy of some discussion. Using either one of these instruments, the regulator is faced with an undesirable behavior by harvesters whenever $\theta \neq \bar{\theta}$, or equivalently, when the regulation chosen is either too lax or too stringent for a given realization of θ.

When $\theta < \theta_L$, e.g. $\theta = \theta_L$ as shown in the diagrams, the problem facing the regulator is the same: harvesters may have a tendency to highgrade, retaining more Y than is contained in the natural catch composition, and discarding Y. On the other side of $\bar{\theta}$, however, the outcome of the two policies differ. Under a value limit, the regulator is assured that the harvester does not discard Y when the regulation binds before the hold is full. Hence, the regulator can impose more stringent limitations on bycatch, as the efficiency costs of being *over*-stringent for some vessels are smaller than under a trip limit.

Trip limits are also problematic in that they require the same (maximum) retention of Y by all vessels, regardless of the realized rate of bycatch. Under a value limit, due to the downward slope of the regulatory constraint, harvesters experiencing higher values of θ are naturally allowed to retain higher amounts of bycatch. This ability of regulators to in effect require different behaviors of different "types" of agents improves the efficiency of the value limit relative to the trip limit.

D. The social planner's problem

The regulator strives to maximize an infinite stream of discounted net benefits by manipulating, in each time m, the three dynamic controls N_{1m}, N_{2m}, and τ_m. The present value (e.g. in time m dollars) arising from the system at time m, assuming an optimal regulatory policy in each time period, is given by the value function

$$V_m\left(X_m, Y_m\right) =$$
$$\max_{N_{1m}, N_{2m}, \tau_m} E_m \sum_{t=m}^{\infty} \rho^{(t-m)} \left\{ p_X R_{1Xt}(\cdot) + p_Y\left[(1-\gamma) R_{1Yt}(\cdot) + R_{2Yt}(\cdot)\right] - c_1 e_{1t}(\cdot) - c_2 e_{2t}(\cdot) \right\}$$

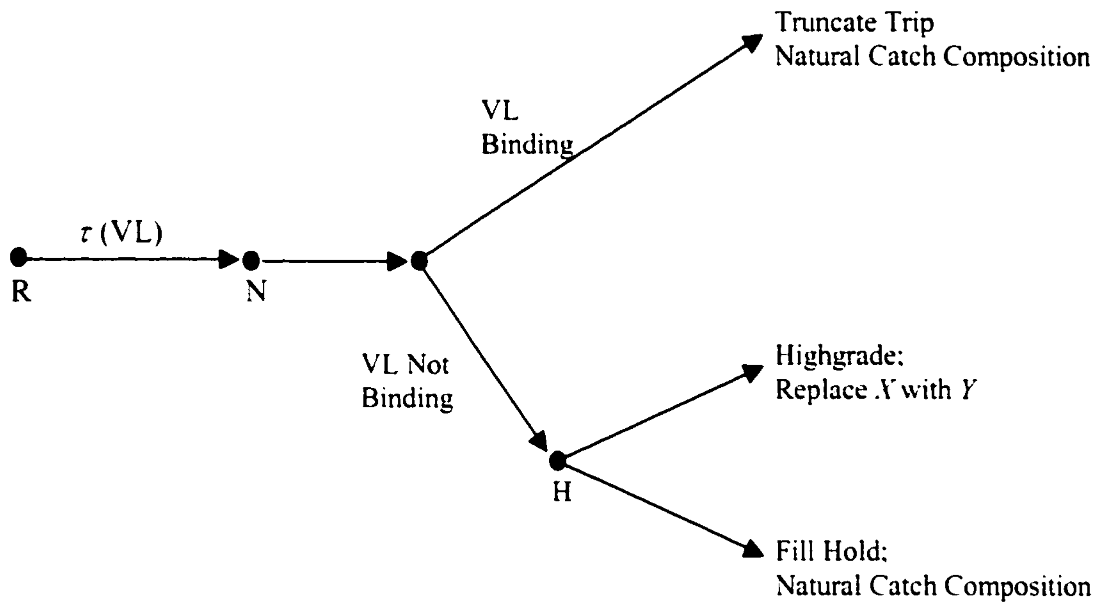

Figure 14: Decision tree for harvesters faced with a value limit on hold contents

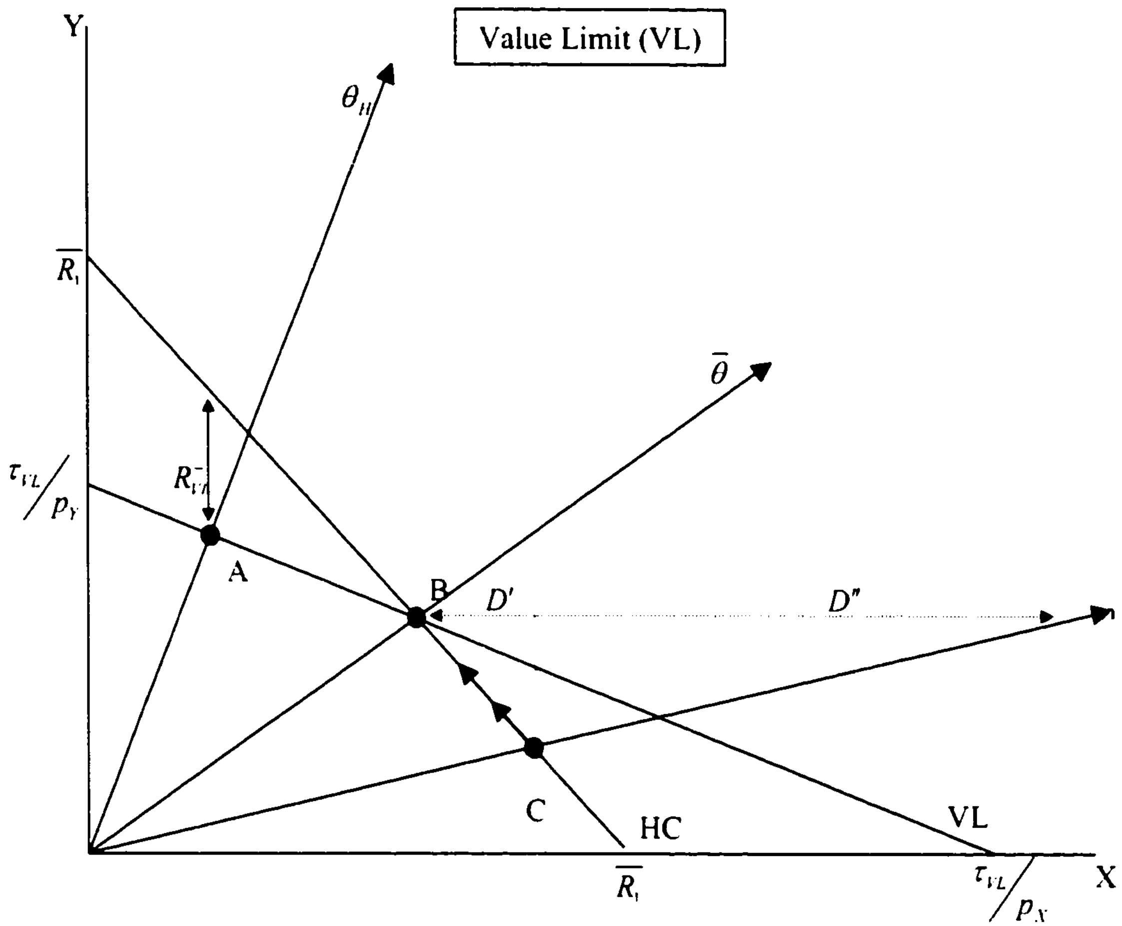

Figure 15: Harvester behavior in response to a value limit τ_{VL}. The line VL represents the maximum catch allowed by the value limit, and HC the hold constraint

where $\rho = 1/(1+\delta)$ is the discount factor, δ is the social rate of discount.

The recursive form of this maximization is

$$\max_{N_1, N_2, \tau} V_m(X_m, Y_m) =$$

(46)
$$E_m\left\{p_X R_{1Xt}(\cdot) + p_Y\left[(1-\gamma)R_{1Yt}(\cdot) + R_{2Yt}(\cdot)\right] - c_1 e_{1t}(\cdot) - c_2 e_{2t}(\cdot)\right\}$$
$$+\rho V_{m+1}(X_{m+1}, Y_{m+1})$$

subject to

(47)
$$X_{m+1} = X_m + r_X X_m\left(1 - \frac{X_m}{K_X}\right) - R_{1Xm}(\cdot) - D_{1Xm}(\cdot)$$
$$Y_{m+1} = Y_m + r_Y Y_m\left(1 - \frac{Y_m}{K_Y}\right) - R_{1Ym}(\cdot) - D_{1Ym}(\cdot) - R_{2Ym}(\cdot)$$

In principal one could substitute the response functions given in (36) and (37) into (46) and (47), and derive first-order conditions for a maximizing set of policy variables at time m. These first-order conditions could then be solved for a dynamic policy function to achieve optimal results.

The difficulty with an analytical solution lies in the fact that the response variables (levels of retained and discarded biomass, $R.(\square)$ and $D.(\square)$) are not continuous functions of the policy parameters: Marginal changes in the policy parameters – in particular, the stringency of the bycatch control instrument τ_m – can cause the choice variables to change discontinuously. For example, a given vessel never discards both X and Y on a given trip, and if all vessels were to experience the same realization of the random bycatch parameter θ_{1jm}, then either D_{1Xm} or D_{1Ym} would be zero. A tax on bycatch, once it exceeds a critical level (as discussed above) causes harvesters who were previously highgrading in favor of Y to cease this action altogether.

Optimization therefore involves more than deriving and solving straightforward first-order conditions; an analytical solution would require separate conditions for each of the continuous and differentiable pieces of the response surface, as a function of the regulatory vector. There may be multiple local optima (either "corner solutions" – at the boundary of one of the pieces – or internal optima) and the regulator should choose the local optimum that gives the highest benefits.

Due to the discontinuous nature of the value function, I do not attempt to derive analytical conditions for an optimum. In the next section, I solve the problem using a numerical dynamic programming technique in order to address a number of questions about the performance of the various potential regulatory policies in different settings.

E. Dynamic programming simulation

As discussed above, analytical treatment of the stochastic bycatch system is limited by the complexity of the system, in particular by the discontinuity in harvester responses to regulations. I developed a numerical dynamic programming routine to characterize the behavior of the stochastic bycatch system and analyze the relative performance of different regulatory policies. In particular, I wish to address such questions as

- Is it optimal to encourage bycatch (i.e. elicit discarding of X in favor of Y) via a subsidy for certain stock levels of X and Y? This might be true when stocks of both X and Y are high, and Y is much more valuable than X, so that it is in the regulator's interest to drive Y to its singular level as fast as possible.

- Do price instruments dominate vessel-based quotas for all starting conditions?

- What is the cost of nonselective fishing effort, relative to first-best exploitation? What loss in productivity of effort would be offset by a given increase in selectivity?

- How does the discount rate affect the relative benefits accruing to different policies? Does this relationship depend on the initial endowment of stocks?

The simulation is coded in Visual Basic and embedded in Microsoft Excel, which serves as the interface for entering parameters as well as for recording and displaying results in tabular and graphical format. Parameters describing the biology and economics of the multispecies system, as well as parameters specifying the resolution and characteristics of the simulation itself, are entered through a parameter worksheet. The routine takes as input all the requisite biological and economic parameters of the model: growth rates, carrying capacities, prices, wages, fixed costs, and catchability coefficients. In addition, the distribution of the stochastic bycatch parameter is entered, either in the form of the endpoints of a uniform distribution or as the values and probabilities of an explicit multinomial distribution. Other distributions could be easily encoded as well.

The simulation is coded in discrete time, though the time step can be set to less than unity if an approximation of continuous-time dynamics is desired. The routine can best be described as an iterative search process, since the parameter space is exhaustively searched for the best action contingent on each set of state variables. The code is designed so as to allow for modifications of the biological and economic assumptions, as discussed in the Conclusions below.

The algorithm for the dynamic programming routine mimics the intertemporal maximization problem presented in (46)-(47). Pseudo-code for the simulation procedure itself is given in . The routine works backward through time, starting at the terminal time *T*, as follows: At each point in time, loop through the elements of the state array (a matrix of dimension *nstateX* x *nstateY*). At each state pairing, iterate through the potential regulatory parameters[23]. For each regulatory parameter, compute the expected action of an individual vessel in each fishery contingent on the different possible values of the stochastic

---

[23] If any; this step is skipped if the "No Control," or NC, option is being simulated.

```
DynamicProgramming ( )
    Loop over Time, starting at terminal period T and moving backward

        If Time = T
        Then "Old Values" = 0 for all {X, Y}  (No Salvage Value at Time T)

        Loop Over X
            Loop Over Y

                Reset Previous Best Value to −∞

                Loop Over Regulatory Parameter Value
                    Calc. Expected Actions for a Single Vessel, given
                        f(θ): Retention of X and Y, Discards, Effort,
                        Exit decision
                    Find Vessel Numbers (N1 and N2) that maximize sum of
                        current profits and future values ("Old Values")
                    If this optimized value is better than Previous Best Value,
                        store actions (Parameter Value, N1 and N2)
                Next Regulatory Parameter Value

                Store best actions for this state pairing
                Store maximized value in "New Value" array

            Next Y
        Next X
        Write new values to spreadsheet, then store them as "Old Values"

    Next Time
                        (a) End DynamicProgramming
```

Figure 16: Pseudo-code for dynamic programming simulation routine

bycatch parameter θ. The action of a vessel includes the amount of effort exerted, the retained catch of each stock, and the discarded catch of each stock. Once the expected outcome for a single vessel is computed, the routine searches over vessel number control space, a matrix consisting of elements

$$\left\{N_1 = 1,\ldots,N_1^{\max}\right\} \mathrm{x} \left\{N_2 = 1,\ldots,N_2^{\max}\right\},$$

with the number of points in this grid (i.e. the resolution of the sampled stock space) specified in the parameter set. For each combination of vessel numbers, the routine computes (i) the aggregate profit accruing to this number of vessels and (ii) the amount of stock of each type that will be available in the subsequent period, following withdrawals and subsequent stock growth.

The optimal behavior for a given stock pairing is the one that maximizes the sum of current expected profits and the (discounted) value of the stock inherited by the following time period, i.e.

$$\left\{\tau_t^*(X_t,Y_t), N_{1t}^*(X_t,Y_t), N_{2t}^*(X_t,Y_t)\right\} = \arg\max E_\theta\left[V_t\left(\tau_t, N_{1t}, N_{2t} \mid X_t, Y_t\right)\right]$$

where the value function V_t at time t, given stock levels (X_t, Y_t), is defined as

$$V_t\left(\tau_t, N_{1t}, N_{2t} \mid X_t, Y_t\right) = \Pi\left(\tau_t, N_{1t}, N_{2t} \mid X_t, Y_t\right) + \rho V_{t+1}\left(X_{t+1}, Y_{t+1}\right)$$

with stock transition equations given as in (47).

The recursion in the algorithm is broken by the absence of a "salvage value" in the final period:

$$V_{T+1}\left(\tau_{T+1}, N_{1T+1}, N_{2T+1} \mid X_{T+1}, Y_{T+1}\right) = 0 \quad \forall X_{T+1}, Y_{T+1}$$

The absence of a salvage value leads to a "mining" behavior towards the end of the time horizon, though – due to positive discounting – this behavior does not significantly affect the behavior of the system or the choice of regulatory variables in earlier time periods. I ignore the mining phenomenon in my analysis. The zero salvage value assumption could easily be changed to reflect some sort of existence value or other consideration if deemed appropriate.

The future stock values $\left(X_{t+1}, Y_{t+1}\right)$ almost invariably fall in between the stock levels for which future values are stored in the future value matrix, i.e. it is often the case that

$$X_L < X_{t+1} < X_H; \qquad Y_L < Y_{t+1} < Y_H$$

where X_L, X_H, Y_L, Y_H are points on the stock matrix grid. A linear interpolation algorithm is used to compute the value corresponding to the intermediate stock pairing:

Suppose that the values corresponding to the four enclosing points on the stock grid are given by

$$V_{t+1}(X_L, Y_L) = V_{LL};\quad V_{t+1}(X_H, Y_L) = V_{HL};\quad V_{t+1}(X_L, Y_H) = V_{LH};\quad V_{t+1}(X_H, Y_H) = V_{HH}$$

The routine first interpolates along the horizontal (X) dimension by computing

$$V'_{t+1} = V_{LL} + \frac{(X_{t+1} - X_L)}{(X_H - X_L)}(V_{HL} - V_{LL})$$

$$V''_{t+1} = V_{LH} + \frac{(X_{t+1} - X_L)}{(X_H - X_L)}(V_{HH} - V_{LH})$$

and then interpolating between these two values along the Y dimension to obtain the estimated value

$$\hat{V}_{t+1}(X_{t+1}, Y_{t+1}) = V'_{t+1} + \frac{(Y_{t+1} - Y_L)}{(Y_H - Y_L)}(V''_{t+1} - V'_{t+1})$$

The value surface is actually a concave, not planar, surface, so that the linear interpolation tends to underestimate the value associated with an intermediate point. However, the linear interpolation routine is a reasonable approximation within a four-point neighborhood if the resolution of the stock matrix is sufficiently high[24].

---

[24] If the resolution of the stock matrix is low, or if the surface is highly curved, then the interpolation routine could easily be modified to a quadratic routine that incorporates the average curvature of the value surface.

At each time step, the simulator records results in the spreadsheet: For each of the stock pairings in the stock grid, the optimal controls N_{1t}, N_{2t}, and τ_t are recorded, as well as the maximized present value arising from the stocks. Below, I analyze these results for a range of different simulation scenarios in order to better characterize the behavior of the system and to draw conclusions about the relative performance of different policy instruments.

F. Simulation Results

The main focus of my analysis of simulation results is the Present Value matrix in the initial time period ($V_0(X_0, Y_0)$ for $X_0 \in [0, K_X]$, $Y_0 \in [0, K_Y]$). This matrix contains the value arising from different initial stock levels, given optimal use of these stocks (within the assumed regulatory constraints) over the entire time horizon. A comparison of this initial value matrix for different regulatory instruments allows for evaluation of the effect of regulatory instruments and different system parameters on the benefits arising from the resource.

1. Base parameters

For purposes of comparison, I use a Base Parameter Set (BPS), summarized in Table 5. The BPS depicts a system in which stock *X*, the target stock of F1 vessels, has a relatively large carrying capacity (four times that of *Y*). Intrinsic growth rates of the two stocks are the same ($r = g = 0.4$). Stock Y has a market price twice that of X, and F1 vessels receive 10% less for harvested Y than do F2 vessels (i.e. $\gamma = 0.1$).

Catchability coefficients for the target stock of each fishery (i.e. q_{1X} and q_{2Y}) are set at 0.000003, an order of magnitude reasonable for empirically observed catch rates in the West Coast Ground Fishery. For example, suppose the biomass level of one of these stocks is 400,000 tons. A reasonable yield for a medium-sized vessel in this fishery is 20,000 pounds (10 tons) in an eight hour tow. Using a Schaefer harvest function, $h = qEX$, this catch rate implies $q = 10/(400{,}000 \cdot 8) = 0.0000031$.

Catchability for bycatch of Y by F1 vessels (q_{1Y}) is set (somewhat arbitrarily) at one third that of the catchability coefficient of X. Wage rates in both F1 and F2 are set at \$20, which can be thought of as an hourly wage rate. Fixed costs for vessels in both fisheries are set at \$3000 per vessel trip, which includes fuel costs, time preparing for the trip, mortgage payments on vessels, etc. The importance of the assumptions made in the parameter set can be explored using the "Batch Simulation" procedure described below.

NPV arising from the resource in all regulatory scenarios is increasing and concave in both X_0 and Y_0. The NPV surface for the BPS in the absence of a bycatch regulation is given in Figure 17. The analysis that follows focuses primarily on this initial value matrix, and how its height varies with the regulatory policy employed and the assumptions made about system parameters. Different policies have different impacts on NPV depending on the initial stock levels; the goal of the analysis is to characterize the relative importance of different policy decisions as a function of the initial stocks inherited by the policymaker.

Before any comparison of different forms of regulation, I examine the implications of technical interdependence between the two stocks. Due to the incentives the F1 vessels have to engage in wasteful discarding behavior, one would expect the benefits provided by the resource to be lower when the two stocks are linked through nonselective harvest. That is, the "bycatch problem" is a costly one; its cost can be explored using the Net Present Value matrix under the two scenarios. I ran one simulation with perfectly selective harvest effort by F1 vessels ($q_{1Y} = 0$), and one with the BPS value of $q_{1Y}^{BPS} = 0.000001$.

2. The cost of technical interdependence

Figure 18 shows the NPV arising from the perfectly selective case as a proportion of the NPV with the standard bycatch level. For all cases where both stock levels are initially greater than zero, the perfectly selective effort case outperforms the nonselective case substantially, with $NPV_{q_{1Y}=0}$ exceeding $NPV_{q_{1Y}=q_{1Y}^{BPS}}$ by between 27 and 46%. The largest benefits of selectivity are realized for high starting-stock levels. In general, as the starting stock level of Y gets larger, selectivity of effort is more important; with

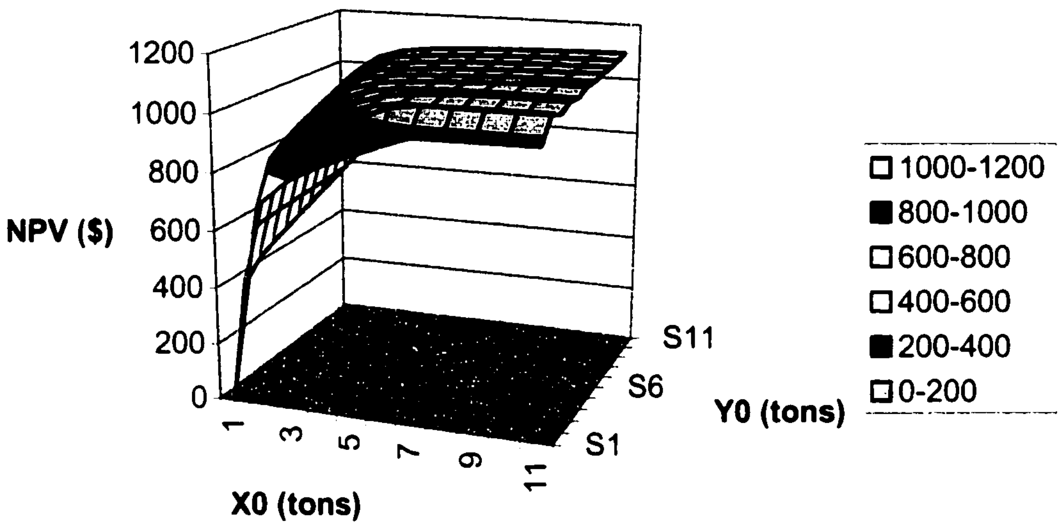

Figure 17: Initial value matrix (NPV_0) arising from BPS with no bycatch control (NC case).

larger Y_0, more of the NPV comes from harvest of *Y*, so bycatch and discarding which reduce these benefits are more significant. This relationship is more pronounced for large starting stock levels of *X*, since with high *X* stock levels discarding of *X* in the case of nonselective effort implies a larger loss in NPV.

3. Harvest intensities under selective and nonselective effort

When no explicit constraint on the retention of bycatch of *Y* by F1 vessels is feasible, the regulator mitigates the negative impacts of discarding by constraining the number of vessel trips taken (N_1 and N_2) in the two fisheries. I compare the optimal number of vessel outings in F1 and F2 under conditions of selective and nonselective effort.

When effort is perfectly selective (i.e. $q_{1Y} = 0$), the two stocks are in essence managed separately: The intensity of F1 effort (i.e. the aspect of such effort under the control of the regulator, the optimal number of vessel trips allowed, *N*1*) depends solely on the biomass of stock *X*, and *N*2* depends solely on the biomass of *Y*. The levels of effort are typical of the "bang-bang" solution for the single-species Schaefer model: Above a certain stock level in each fishery, maximum harvest intensity is allowed; below a

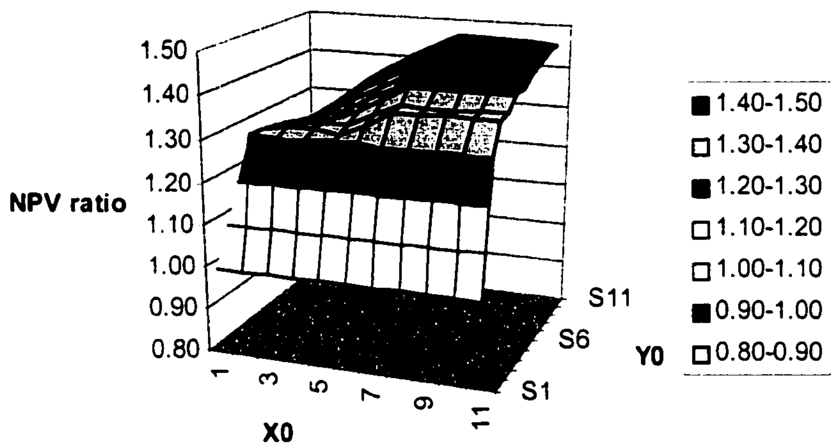

Figure 18: NPV from perfectly selective F1 harvesting, relative to NPV from non-selective harvesting ($q_{1Y} = 0.000001$).

critical level, harvest is prohibited; and in between these two levels (theoretically for a single steady-state biomass level), some internally optimal "singular control" is used. Figure 19, panels (a) and (b) show the optimized number of vessel trips, $N1$ and $N2$, for the case of perfectly selective effort.

When effort is nonselective, trips taken by F1 vessels have additional social cost in the form of both discarded X (due to highgrading) and inefficient use of harvested Y. The former cost arises as long as the stock of Y is sufficiently high to elicit discarding by at least some of the F1 vessels. Inefficient use of Y is most problematic for intermediate levels of Y: When Y is small, profitability of harvesting Y is too low to elicit highgrading by F1 vessels. When Y is large, harvest of Y by F1 is actually useful in driving Y towards its dynamically optimal level.

The regulator responds in general by reducing the number of F1 vessels. In particular, $N1$ is reduced dramatically from $N1_{max}$ for intermediate levels of Y, even when X is large. For these intermediate levels of Y, the F2 fishery is capable of extracting the optimal level of Y, so interference by the less efficient F1 is undesirable. Beyond a small number of F1 vessels, the costs of additional F1 vessels outweighs their benefits.

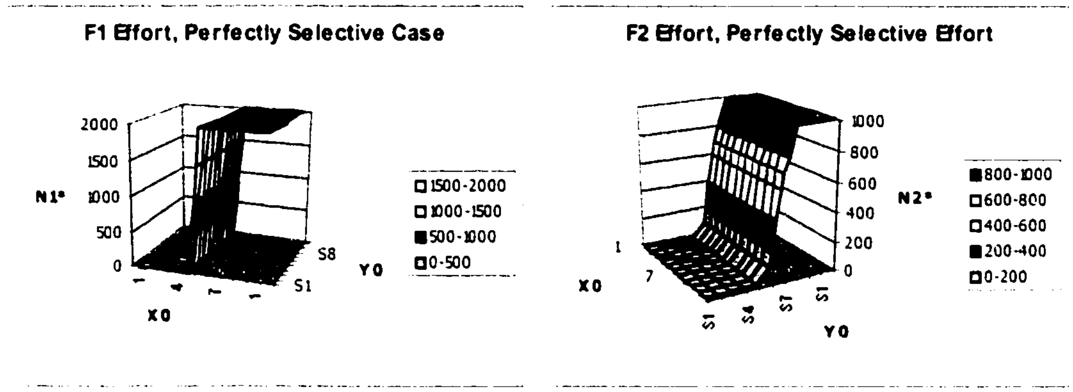

Figure 19: Optimal effort levels (vessel trips) vs. starting stock levels in case of perfectly selective effort. Panel (a) shows effort in F1, (b) in F2. This simulation was run using $N_1^{max} = 2000$, $N_2^{max} = 1000$.

For very small values of Y, any benefits deriving from the Y stock occur in the distant future, and are thus heavily discounted. N_1 is reduced but only slightly, as the benefits of F1 vessels outweigh to a large extent the benefit of protecting the highly depleted Y stock. For very large values of Y, the F1 vessels are allowed to function almost to the level in the selective effort case, since Y is overabundant and harvest by the F1 vessels is not that detrimental. Figure 20, panels (a) and (b) show the optimal vessel numbers in the nonselective effort case for F1 and F2 respectively.

Figure 21 illustrates the relationship between catchability of Y by F1 vessels and the NPV arising from the two-species system, when no bycatch control is used: NPV is given for a range of catchabilities from 0 to 0.00001 (10 times that of the BPS level for four different initial stock pairings: LL ($X_0 = 0.1K_X$, $Y_0 = 0.1K_Y$); HL ($X_0 = K_X$, $Y_0 = 0.1K_Y$); LH ($X_0 = 0.1K_X$, $Y_0 = K_Y$); and HH ($X_0 = K_X$, $Y_0 = K_Y$). As the mean catchability coefficient (parameterized by q_{1Y}) increases, NPV of the resource decreases monotonically until the point at which it is preferable to shut down the F1 fishery altogether. Clearly, as catchability of Y by F1 increases beyond this point, NPV is unchanged. For the initially unexploited system (HH), NPV declines to a point and then actually rises again; More efficient harvest of Y is beneficial after some point, as long as both stocks are initially large, and are "mined" initially. This analysis indicates the potential benefits of investment in more selective fishing gear, such as the Nordmore Grate or other excluder devices. However, the benefits in such investment are non-

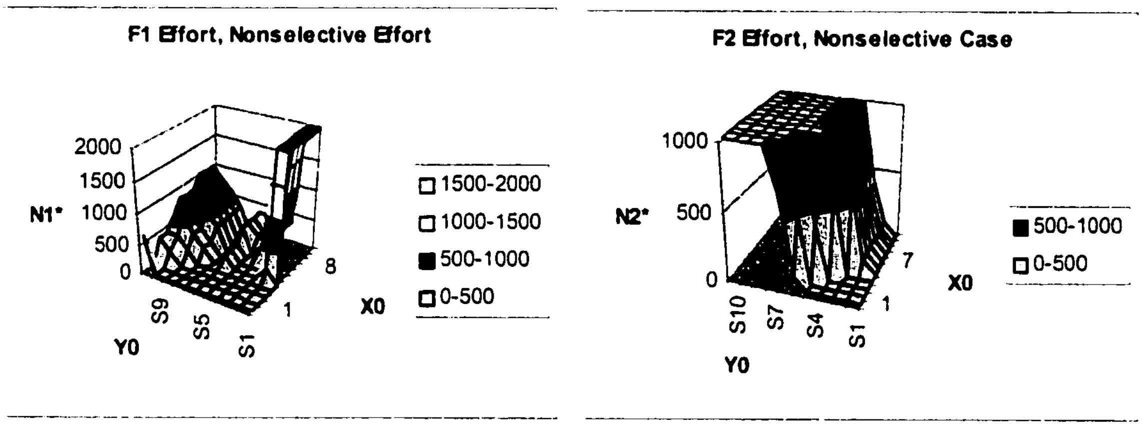

Figure 20: Optimal effort levels (vessel trips) vs. starting stock levels in case of nonselective effort (q_{ij} = 0.000001). Panel (a) shows effort in F1, (b) in F2.

convex over some ranges, i.e. increasing selectivity has zero marginal benefit until a critical threshold is passed.

The comparative static analysis with respect to the mean catchability of Y by F1, q_{1Y}, can be used to derive a willingness-to-pay schedule for marginal improvements in selectivity. Such a result presumes that selectivity with respect to Y can be achieved without altering the catchability of X by F1. This is unlikely to be the case, as any measure that successfully reduces the catch of one stock is likely to reduce that of the other as well. Certainly this correlation in catchabilities is an issue when mesh size is used as a selection device, and even behavioral exclusion devices such as Nordmore grates and excluder devices are likely to decrease catch of the target species as well.

I address the issue of catchability correlation by examining the value surface as a function of different catchabilities of X and Y by F1. Figure 22 shows contours of the value surface of a virgin stock as a function of different values of q_{1X} and q_{1Y}, under a tax on bycatch (scenario TX). Value increases as q_{1X} increases and as q_{1Y} decreases.

The slope of the contours represents the social marginal rate of substitution between catchability of Y and catchability of X, i.e. they imply how much lost efficiency in harvest of X society should be willing to forgo in order to improve selectivity vis-à-vis Y. The contours are upward-sloping because catchability of Y by F1 is in general a "bad."

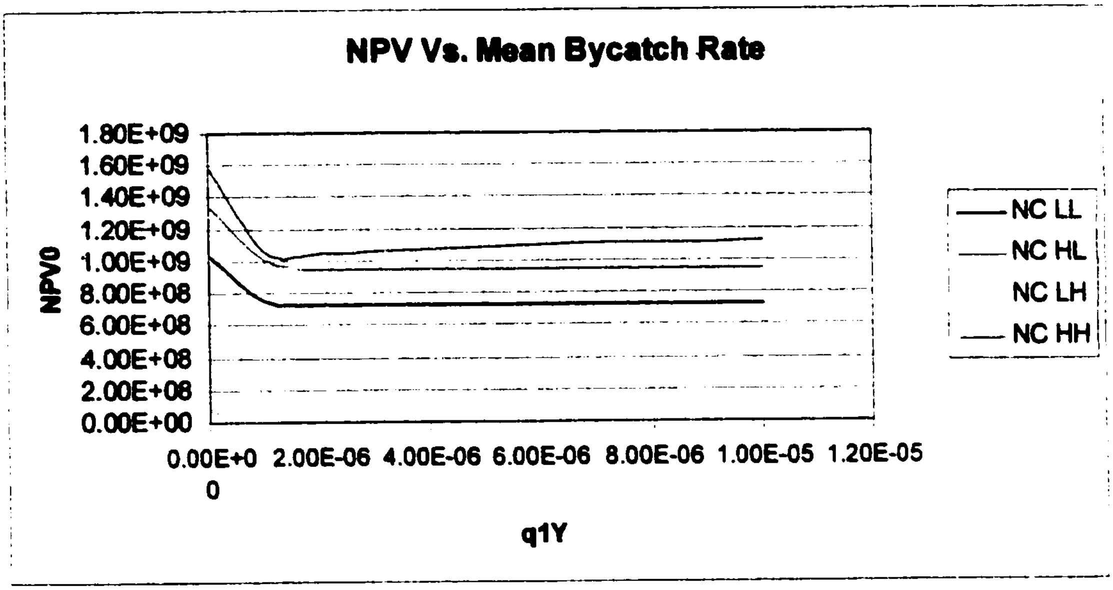

Figure 21: NPV Vs. mean catchability of *Y* by F1 vessels, for four different starting stock pairings.

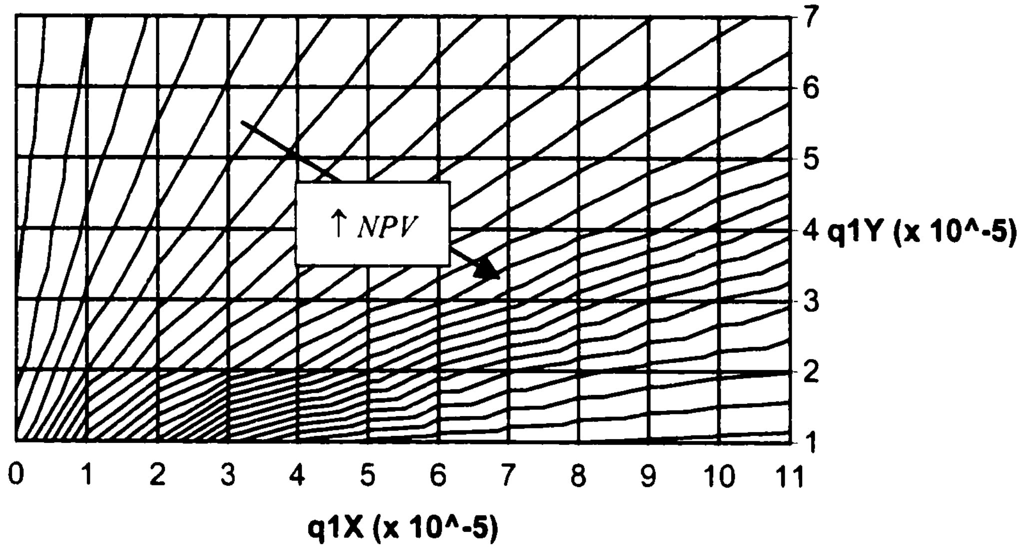

Figure 22: Contours of the NPV surface, under TX scenario, for different F1 catchability coefficients.

4. Comparison of policy performance

The performance of different regulatory policies can be compared on the basis of the initial (t = 0) value matrix produced by a given scenario. The advantage conferred by any given policy may be different – qualitatively or quantitatively – for different starting stock levels or different parameter values; that is, one type of policy may be much better for a virgin stock, and only marginally better when both stocks are severely depleted.

Table 6 shows the NPV arising under the four different candidate policies NC, TL, VL, and TX. Results are reported for the four different starting stock scenarios LL, HL, LH, and HH defined above. An important result emerging from this simple experiment is the consistent ordinal relationship between the performance of the different policies: Price instruments (TX) provide the highest NPV under all initial stock conditions, followed by Value Limits (VL), Trip Limits (TL), and unconstrained bycatch (NC) in order of decreasing NPV.

The consistent rank ordering of the policies has intuitive appeal. Without a bycatch control, the regulator must take into account both the socially undesirable highgrading (i.e. discarding X in favor of Y), as well as the F1 vessels' inefficient use of Y. To mitigate these effects, the regulator severely reduces F1 effort ($N1$) from its technically independent level. Suboptimal use of both stocks arises, and significant informational rent is given to the harvesters under conditions of stochastic bycatch.

Under a trip limit, the regulator can constrain the degree of highgrading by imposing a maximum on retained bycatch. However, when the bycatch level is uncertain, it is never possible to impose the optimal trip limit on every vessel. Vessels that naturally experience high rates of bycatch either discard valuable Y in order to comply with the trip limit, or choose to truncate their trip before filling their hold, whichever is more profitable; and vessels experiencing lower levels of bycatch than presumed by the trip limit may find it advantageous to highgrade, i.e. pad their hold with Y (discarding the X that is concurrently harvested) until their trip limit becomes binding.

With a value limit, the dilemma faced by regulators is similar: The "optimal value limit," if discarding is unequivocally undesirable, is the one which equals the market value of a hold full of the naturally occurring catch composition. When that natural catch composition is a random process, a single value limit can never be "optimal" for all vessels.

The difference between Trip Limits and Value Limits arises when the imposed value limit is binding: Once a trip limit is reached, the harvester may have an incentive to continue harvesting, retaining only X and discarding any Y caught. Under a value limit, no such incentive ever exists: If the harvester cannot legally increase the revenue arising from their hold, then the trip is truncated upon fulfillment of the value quota. Selective retention of X is eliminated as a possible behavior. Value limits are still subject to the problem of highgrading by those harvesters receiving a lower-than-expected bycatch rate, as long as that bycatch rate is sufficiently high to make such highgrading possible.

Under a price instrument, as illustrated in Figure 10, it is always possible to set the tax so as to eliminate any kind of discarding behavior; it is always possible for the regulator to charge τ_M, i.e. take the middle arm from their decision node[25]. This causes harvesters to fill their hold with the natural catch composition *regardless* of the realization of the random bycatch parameter θ. If it is optimal for some reason, the regulator *can* either charge a high tax to elicit discarding of *Y* in favor of *X*, or a low tax to elicit discarding of *Y*. Anecdotally, neither of these strategies of inducing discarding are chosen for any starting stock levels in any of the policy scenarios I examine.

Different policies have different costs, so it is not sufficient to know simply the ordinal ranking of policy performance. It is also important to know the *magnitude* of superiority of one policy to others, and understand what characteristics of the system make the disparities between policies larger or smaller. In the following section I use sequences of simulations to characterize the sensitivity of relative performance of policies with respect to different system parameters.

---

[25] In fact, τ_M is not a single value but a range of values of the price instrument such that the harvester has no incentive to discard.

I embedded the entire simulation routine in a "batch simulator" to investigate numerically the comparative statics of relative performance of policies. The batch simulator iterates through a number of values of a particular parameter, and records the present values arising from the system for each of the four regulatory scenarios, at each of the four starting stock levels LL, HL, LH, and HH. I carried out such batch simulations for five system parameters: The discount rate (ρ); the coefficient of inefficiency (γ) of F1 vessels in selling harvested Y ; fixed costs FC_1 and FC_2 associated with vessel trips in F1 and F2 respectively; mean catchability of Y by F1 vessels (q_{1Y}); and the variance of the bycatch parameter θ, represented by the breadth of a uniform distribution centered around $\bar{\theta} = 1$. The results of these batch simulations are summarized and discussed below.

a) Policy performance vs. the discount rate

Net present values under all regulatory scenarios are – not surprisingly – inversely related to the discount rate. In addition, the absolute differences between any two policies decreases with ρ, not surprising since all NPVs tend towards zero as the discount rate gets large Figure 23 shows the relationship between NPVs of different policies and a range of discount rates between 0.01 and 0.08 for starting stock pairings HH.

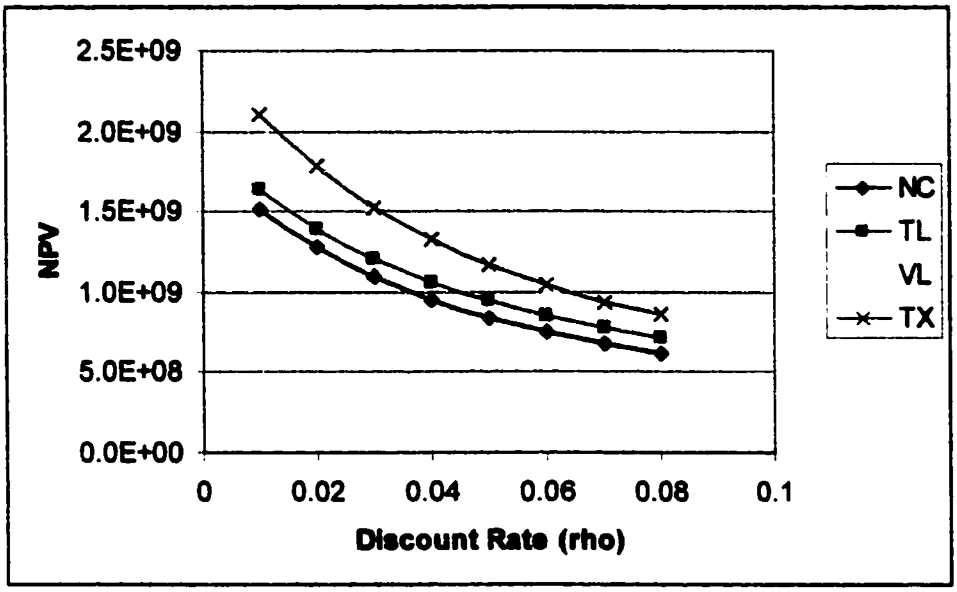

Figure 23: NPV Vs. the discount rate, with HH starting stock levels

Though the trend in NPV for each policy and for the difference between NPVs is straightforward with respect to ρ, an examination of the *relative* NPVs of different policies for different starting stock levels reveals a qualitative difference. For situations in which one stock (LH, HL) or both stocks (LL) are severely depleted, the relative superiority of different policies is diminished as the discount rate increases. For the HL case, for example, where Y is initially severely depleted, the TX scenario yields NPV 28% higher than under the NC case when $\rho = 0.01$. As the discount increases to $\rho = 0.08$, however, the advantage of TX over NC decreases to 16%. Similar trends, though slightly less dramatic, are observed in the HL and LH cases, i.e. where only one stock is initially depleted.

In the HH case, however, the relationship between the NPV_{TX}/NPV_{NC} ratio and the discount rate is different: For $\rho = 0.01$, the TX yields 40% higher NPV than NC. As ρ increases, the advantage of the price instrument declines but only slightly, to 39%, then rises again as the discount rate gets large; see Figure 24. As the initial stock levels get smaller, the downward-sloping relationship between NPV_{TX}/NPV_{NC} and ρ emerges; when starting stock levels are both at 40% of their carrying capacities or lower, the relationship is monotonically downward-sloping.

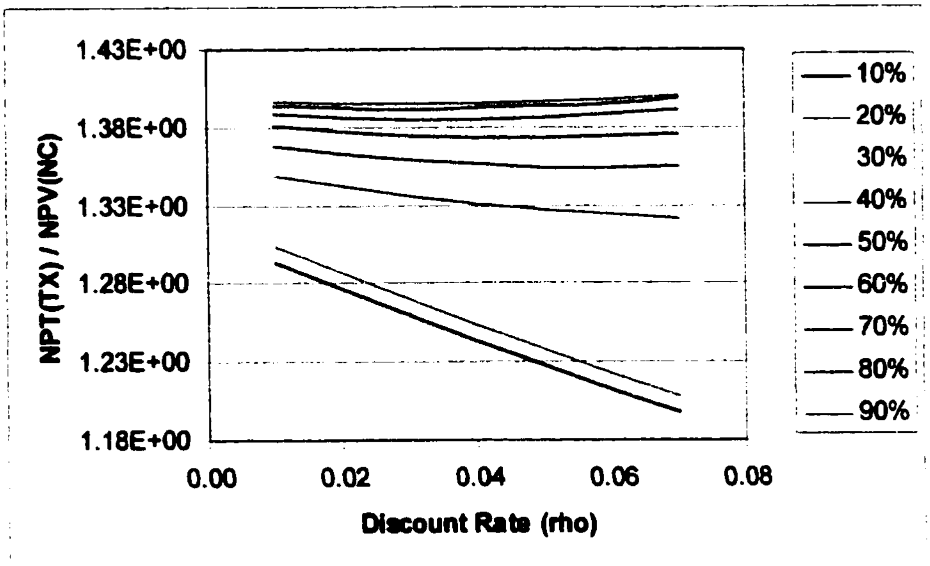

Figure 24: NPV of TX regulation relative to NC vs. the discount rate, for stocks initially at different percentages of respective carrying capacities.

The difference between the relative advantage of the price instrument for different starting stock levels has a subtle explanation: For severely depleted stocks, the general strategy is to leave the stocks alone initially to recover, then begin to harvest once they reach their dynamically optimal steady state values[26]. Hence, as illustrated in its dynamically optimal level.

[26] When the two stocks are linked technically or ecologically, the dynamic path is somewhat more complicated than the simple bang-bang approach I describe here. But the general notion of delaying harvest for some initial period still holds.

Figure 25 panel (a), nominal rents are initially zero and then become positive after some point. The benefits of a superior policy (e.g. a tax) manifest themselves in a more rapid approach to the steady-state optimum and a higher level of rents extracted once this level is reached. For a virgin stock, the system is initially "mined," since biological productivity is low and it is not optimal to hold capital as fish. The objective is to maximize current revenues, cashing out the stock to invest it at the market rate of interest. With high initial stocks, the nominal rents are as illustrated in Figure 25, panel (b): They begin high, and steadily decrease as stocks are driven towards their steady-state optimum. Benefits from this system come both from the ability to extract revenue quickly at first, as well as from the prudent management of the resource once it has equilibrated at its dynamically optimal level.

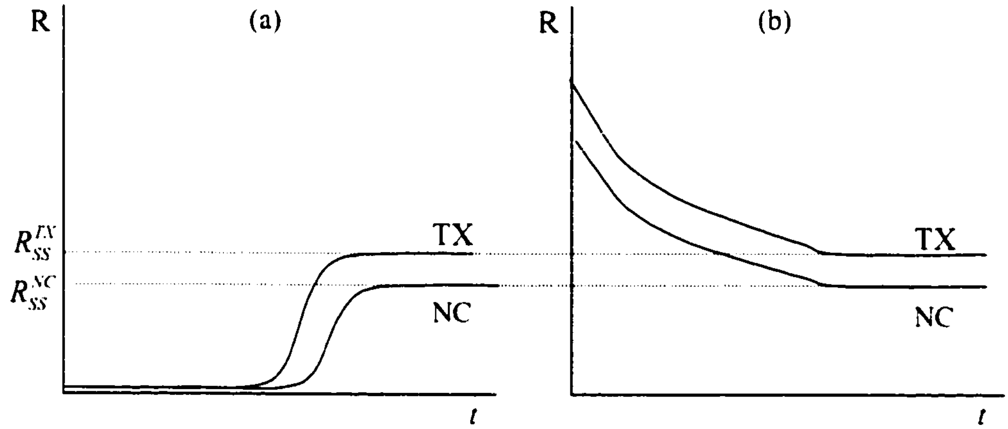

Figure 25: Nominal rents over time under TX and NC for (a) initially depleted and (b) initially plentiful stocks

Higher discount rates therefore affect the present values of these two rent streams differently: In the depleted (LL) stock case, higher discounting drive both NPVs towards zero, and hence their ratio approaches unity. In the HH starting stock case, discounting depresses the NPV but also amplifies the importance of the present. Since there are positive benefits derived from the resource in the initial time period (due to the initial drawing down of stocks), the ratio of these initial benefits is the limit of the NPV ratio as ρ gets large.

b) Policy performance vs. F1 inefficiency in harvest of *Y*

The coefficient of inefficiency, γ, is what makes it socially preferable, *ceteris paribus*, for a unit of *Y* to be harvested by an F2 vessel rather than an F1 vessel. The larger γ, the larger the social loss associated with the retention by F1 of a unit of Y, relative to what could have been obtained if that same unit had been captured by F2. A reasonable intuition might therefore be that net benefits arising from the multispecies system would decline as γ increases. The value of marginal product of F1 effort is lower when one of its outputs is less valuable.

Figure 26 shows NPV for the BPS for a range of values of γ from 0 to 0.8. The results pictured are those from an initially depleted stock of both *X* and *Y* (i.e. initial stock pairing LL). NPV is not downward-sloping in γ for all regulatory scenarios: For the

NC and TL scenarios, NPV increases with γ over a large range of values, then begins to decline after γ reaches a threshold value of 0.5. For the TX and VL policies, NPV declines steadily over the entire range of γ values.

To explain the difference in impacts of γ on benefits, consider the incentive provided by increasing γ. On one hand, increasing γ has a negative impact on society, eroding the value of Y brought to port by F1 vessels. On the other hand, increasing γ decreases the price differential between retained X and Y. This reduces the incentive harvesters have to highgrade in favor of Y, making it less probable that the price differential outweighs the marginal cost of obtaining additional units of Y. This reduces the moral hazard problem vis-à-vis discarding of X, and allows the regulator to control bycatch more strictly. In essence, γ acts as a "tax" on bycatch of Y by F1 vessels. Like a tax, increasing γ reduces their incentive to exert additional effort to augment their holdings of Y.

The beneficial aspect of increasing γ only applies to the NC and TL cases, for these are the only two scenarios in which the regulator cannot set policy so as to eliminate discarding of X. In the VL case, stringent bycatch controls potentially lead to trip truncation, but never to discarding of X, and in the *TX* case neither truncation nor discarding of X takes place.

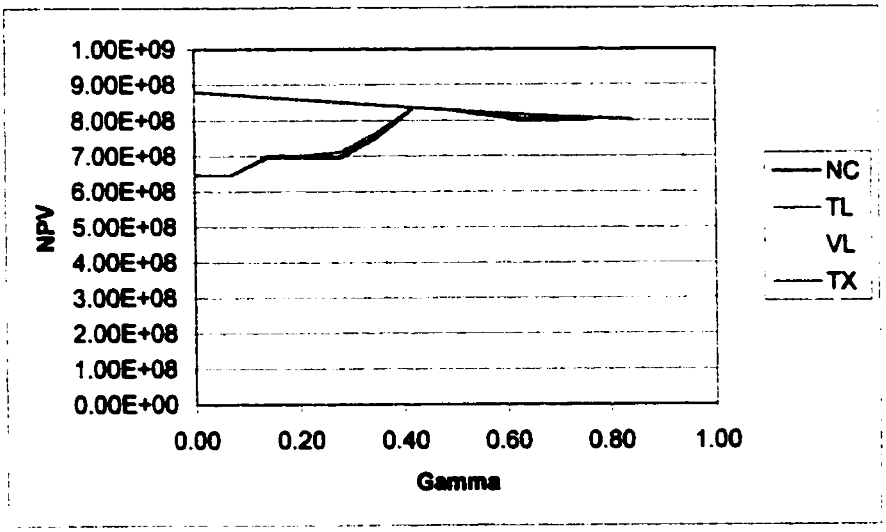

Figure 26: NPV from different policy instruments for different values of γ. Starting stocks at LL (both initially depleted)

c) Policy performance vs. F1 fixed costs

Most bioeconomic models, even those which explicitly incorporate harvester behavior, consider only the marginal cost of harvest effort. Little attention is paid to the existence of fixed costs of vessel ownership and operation, though the costs of steaming to fishing grounds can constitute a large part of average cost of harvest. Anderson includes fixed costs in a recent theoretical piece on vessel behavior in a single-stock fishery [Anderson, 1999 #151]. Fixed costs are likely to be more important for the behavior of vessels in deep-sea fisheries than they are for coastal artisanal industries. In these distant fisheries, it is even more costly for the regulator to monitor harvester behavior, so informational asymmetry is exacerbated.

In this section, I investigate the importance of such fixed costs under conditions of stochastic bycatch, specifically whether changes in the fixed costs of vessels in F1 have implications for relative policy performance.

Figure 27 shows NPV as a function of FC_1 for the four regulatory scenarios. NPV declines with FC_1 for all of the instruments, which is to be expected as the cost of a productive input has increased. There are no benefits associated with changes in behavioral incentives, as increasing fixed costs has no impact on the marginal decisions of harvesters vis-à-vis effort exertion or retention of each of the two stocks.

Despite the monotonic decrease in NPV for all regulations, there are potentially important differences between in the way rising FC_1 impacts NPV across regulatory scenarios. From Figure 27, it is apparent (though not obvious) that NPV under the price instrument (TX) drops off less quickly as FC_1 increases than it does under the other policies.

As FC_1 gets very large, NPV under all policies converges to a common value. Extreme high values of FC_1 make operation of F1 vessels unprofitable, and all NPV arises from harvest of Y by F1 vessels.

Figure 28 shows NPV under the TX scenario relative to NPV arising from unconstrained bycatch and value limits. NPV of taxes rises, relative to these alternative NPVs, as FC_1 rises initially. The possibility of trip truncation under a value limit exacerbates the impact of rising fixed costs. It is important to note that both the relative advantage of TX over the other policies, as well as the absolute dollar-denominated difference between TX and the other policies, grows as FC_1 grows initially, making implementation of a price instrument more cost-effective.

d) **Policy performance vs. variance in bycatch rate**

In order to ascertain the importance of asymmetric information in the stochastic bycatch setting, I examine performance of the various regulatory variables under different probability distributions of the random bycatch parameter θ_{1jt}. θ_{1jt} is assumed to be a

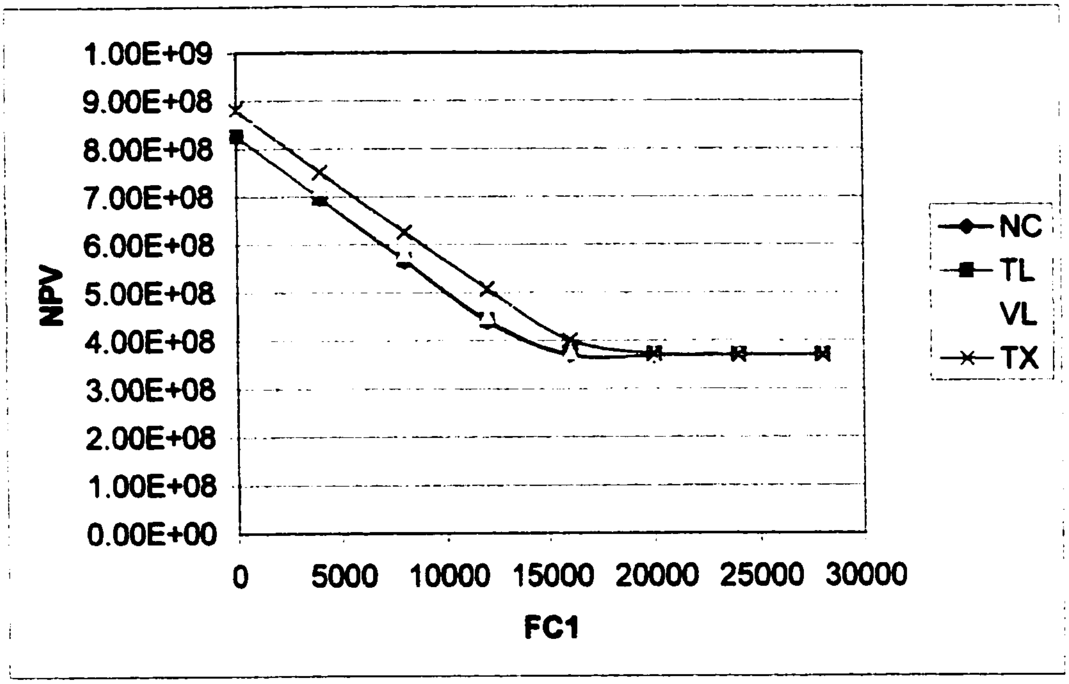

Figure 27: NPV Vs. FC1 for regulatory parameters, given LL starting stocks

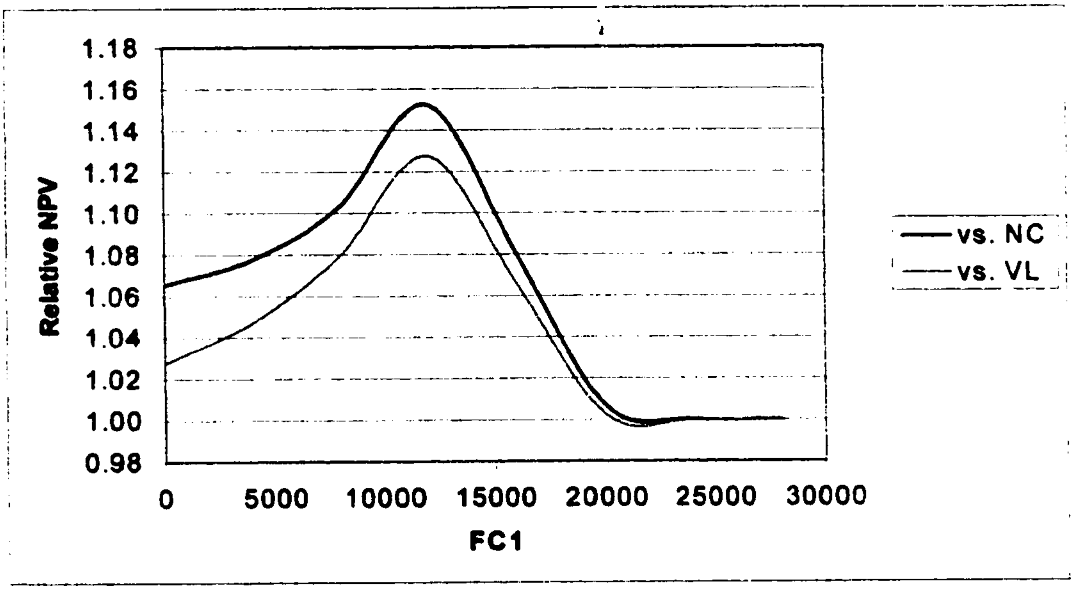

Figure 28: NPV of TX regulation relative to NC and VL, vs. F1 fixed costs

random variable with mean $\mu = 1$ and variance σ^2; I consider eight different uniform distributions $\theta_{1jt} \sim U[a,b]$, each with $(a+b)/2 = 1$. Ranges of these distributions, or the "Theta Spread" (i.e. $b-a$) span from zero to 2.8, reflecting growing variance in bycatch rates. Figure 29 shows the NPV arising from the resource under each of the regulatory parameters for this range of θ_{1jt} distributions.

NPV falls as variance of bycatch rises for all regulatory scenarios except the price instrument. NPV under TX is constant across all distributions of θ_{1jt} considered, because the price instrument used to prevent discarding, for example, depends only on the respective prices of the two stocks and is independent of expectations about θ_{1jt}.

When $b-a=1$ (Theta Spread = 0), the catchability of Y by F1 vessels is equal with certainty to its mean rate of q_{1Y}. In this case, the regulator knows the rate of withdrawal of each stock by each vessel, and also that this rate of withdrawal is equal across vessels. When $\sigma^2 > 0$, the regulator no longer knows with certainty the rate of bycatch by *any* vessel with certainty, and in addition each of the $N1$ vessels in F1 experiences a *different* rate of bycatch; no single trip limit or value limit can elicit first-best behavior (i.e. zero discards, in most cases) on the part of all harvesters. Price instruments (TX), however, *are* capable of eliciting first-best behavior by all harvesters.

The decline in NPV for the VL policy is more gradual than that of the trip limit and unconstrained bycatch cases. This result stems from the fact that the regulator need not be concerned about highgrading in favor of *Y*, so they can impose a more stringent limitation on bycatch.

Figure 30 shows the NPV of the four policies, standardized to the NC case. Clearly, the relative advantage of the VL and TX scenarios grow steadily as uncertainty regarding the bycatch rate increases.

G. Conclusions

This paper develops a model of a two-stock system in which bycatch leads to social inefficiency. Though a number of papers deal with similar issues, I introduce several features which allow for the investigation of questions not treated in the existing literature. Most notably, I combine stochasticity in bycatch with discrepancies between private prices and shadow prices to highlight the moral hazard problem associated with discarding; Androkovich and Stollery, for example, incorporate stochastic bycatch but no discarding.

The second key feature of my model is its depiction of the fleet as consisting of discrete agents who experience different states of nature. This allows me to investigate the impact of regulatory policies not only on harvest rates per unit effort, but on the decisions of harvesters to cut short trips, shut down altogether, or exert extra effort to take full advantage of any leeway provided them by regulations. Heterogeneity of

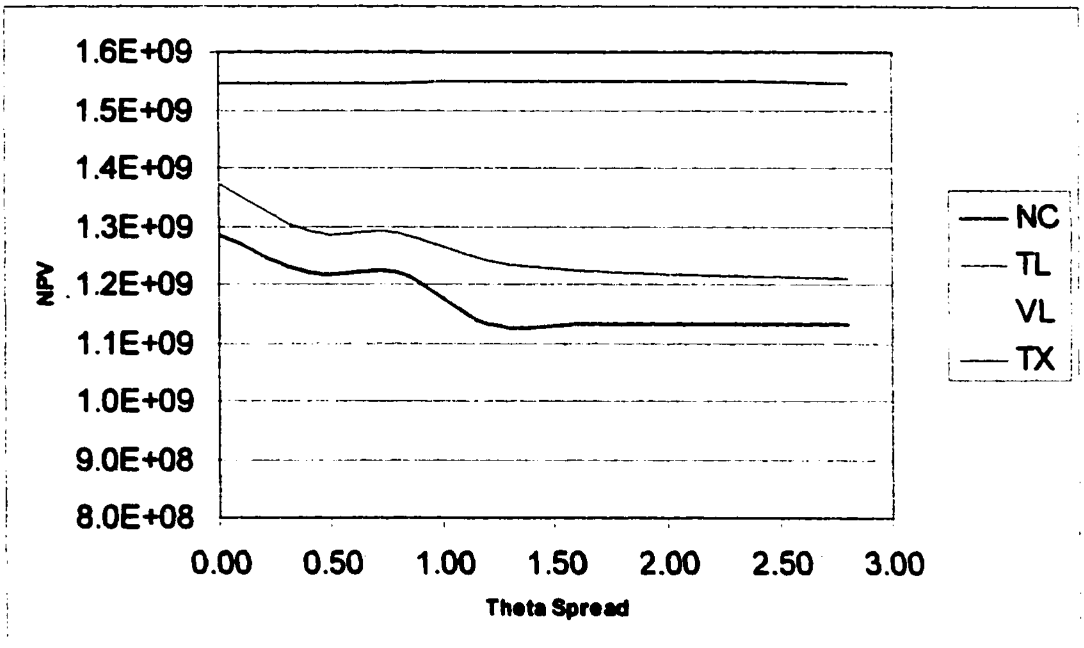

Figure 29: NPV vs. range of uniform distribution of θ_{1jt}, for HH starting stocks

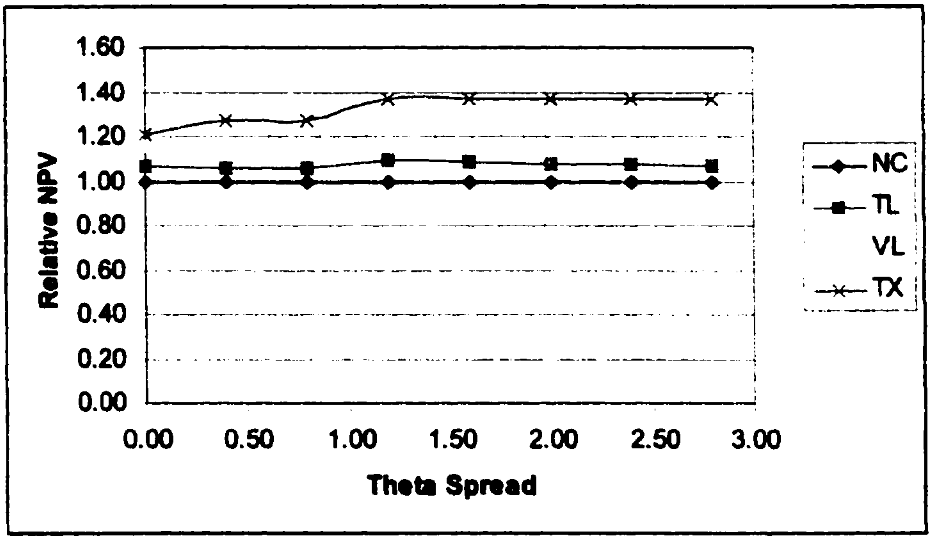

Figure 30: NPV relative to NC regulation vs. range of uniform distribution of θ_{1jt}, for HH starting stocks

catch compositions across vessels is an important source of inefficiency, particularly among policies for which there is a social cost associated with being both too lenient and too strict.

The fundamental result of this paper is the dominance, from an efficiency (NPV) standpoint, of price instruments over vessel-based quotas (either biomass or value limits). Price instruments in the context of this model are able to eliminate discarding in all cases by taxing away the difference between the ex-vessel prices of the two stocks; their efficacy is independent of any knowledge (or lack thereof) regarding the stochastic bycatch process. Both trip and value limits have social costs associated with deviation from the first-best quota for each harvester. It is not possible to determine what quota is optimal for each harvester, and it would be too difficult to implement vessel-specific quotas even if it *were* possible. Therefore the regulator must seek with the quota instruments to jointly minimize two competing costs or, rather, to find the best possible compromise between them.

Value limits are consistently superior to trip limits, since they effectively eliminate discarding of X in favor of Y, and because they allow harvesters with higher natural catch of Y per unit effort to retain more of that stock.

Interestingly, trip limits are perhaps the second-most prevalent regulatory scenario in the real world, following NC. They are used extensively in the West Coast Groundfish resource, as well as in the multispecies fisheries of the Northwest Atlantic. This may be because trip limits are relatively low-cost to implement and enforce. The benefits of increased compliance might outweigh the theoretical deficiency in NPV, but this is an empirical question beyond the scope of this study.

Other compelling results of this paper involve the sensitivity of regulatory performance to parameter values. Such information could be of interest to a regulator deciding between the regulatory approaches. In particular, I find the coefficient of inefficiency (γ) to be – somewhat counterintuitively – of help to the regulator who employs either a trip limit or no bycatch control at all. γ serves as a self-regulation device under these policies and mitigates the tendency to highgrade for Y. Price instruments and value limits already resolve that problem, so γ is of no benefit under these regulations; in fact it is detrimental to NPV for the F1 vessels to have the marginal product diminished at all.

Fixed costs associated with vessel trips also impact the benefits of the resource and the relative performance of different policies. In particular, the presence of fixed costs amplifies the efficiency benefits conveyed by price instruments, which do not elicit trip truncation behavior. This fact has important policy implications for fisheries in which fishing effort drives down stocks over time and forces harvesters to steam further from port. As these transportation costs rise, the implications of trip truncation for average costs of harvest are magnified. These results are not forthcoming from models in the literature which either use pooled effort representations or assume away fixed costs.

I find that availability of the incidentally caught stock to fishing effort is a bad, since it provides an incentive for harvesters to engage in wasteful discarding behavior. *Ceteris* paribus, the regulator would like to reduce the availability of the non-target species. However, such invulnerability usually comes at a cost, namely the reduced availability of the *target* stock to the same fishing effort. The structure of the model and the simulation algorithm make it straightforward to compute the rate at which the planner should be willing to sacrifice catchability of the intended stock in order to marginally reduce catchability of incidentally caught organisms.

Lastly, I find that the starting stock levels inherited by the social planner affect the comparison between policies, so that in theory different regulatory instruments might be chosen given different initial endowments of stock. For example, the relative benefits of prices over other policies diminish montonically with the discount rate if one or both stocks are initially low, but remain fairly constant with respect to the discount rate when stocks start out healthy.

Clearly, many considerations enter into the choice of regulatory policies, only one of which is the relative pecuniary (efficiency) benefits: Some regulations are difficult or costly to implement, others to enforce. Some engender resentment among harvesters and lead to political difficulties, and still others might be unacceptable due to the financial burden they impose on liquidity-constrained harvesters. I do not address any of these issues in this paper, but rather strive to provide a framework for ascertaining the determinants, magnitude of discrepancies between the economic benefits arising from a multispecies resource.

H. Tables

Table 5: The Base Parameter Set (BPS)

Stock-specific Description	**Stock X** Name	Value	**Stock Y** Name	Value
Growth rate	r	0.4	g	0.4
Carrying capacity (tons)	K	400000	L	100000
Catchability by F1	q_{1X}	0.000003	q_{1Y}	0.000001
Catchability by F2	q_{2X}	0	q_{2Y}	0.000003
Price ($/ton)	p_X	1200	p_Y	2400

Fishery-specific Description	**Fishery 1 (F1)** Name	Value	**Fishery 2 (F2)** Name	Value
Hold capacity (tons)	$\overline{R}_1$	20	$\overline{R}_2$	20
Wage ($/effort hour)	w_1	20	w_2	20
Fixed costs ($)	FC_1	3000	FC_2	3000
Max # vessels	N_1^{max}	2000	N_1^{max}	1000
Diminution of bycatch value	γ	0.1	---	---

General Description	Name	Value
Discount Rate	ρ	0.03

Table 6: NPV for the BPS parameters for the four different regulatory policies. NPV measured in $100,000's, computed over a 40-period time horizon.

Policy	Starting Stock Pairing			
	NC	TL	VL	TX
LL	8.37	8.42	10.21	10.55
HL	10.55	10.80	12.73	13.08
LH	10.26	10.44	12.41	12.75
HH	10.94	12.08	14.81	15.26

Table 7: Conditions for behavior of harvesters with no constraint on retained bycatch R_{1jYt}, and associated choice variables for each of the possible behaviors

Behavior	Conditions	e_{1jt}	R_{1jXt}	R_{1jYt}	D_{1jXt}	D_{1jYt}
No discards, full hold	$-MC_{1X} \le (1-\gamma)p_Y - p_X \le MC_{1Y}$	$\frac{\overline{R_1}}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}$	$\overline{R_1}\left(\frac{q_{1X}X_t}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}\right)$	$\overline{R_1}\left(\frac{q_{1Y}Y_t}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}\right)$	0	0
No discards, trip truncated	$c_1 > p_X q_{1X}X_t + (1-\gamma)p_Y\theta_{1jt}q_{1Y}Y_t$	0	0	0	0	0
Discard X for Y	$(1-\gamma)p_Y - p_X > MC_{1Y}$	$\frac{\overline{R_1}}{\theta_{1jt}q_{1Y}Y_t}$	0	$\overline{R_1}$	$\frac{\overline{R_1}q_{1X}X_t}{\theta_{1jt}q_{1Y}Y_t}$	0
Discard Y for X	$p_X - (1-\gamma)p_Y > MC_{1X}$	$\frac{\overline{R_1}}{q_{1X}X_t}$	$\overline{R_1}$	0	0	$\frac{\overline{R_1}\theta_{1jt}q_{1Y}}{q_{1X}X_t}$

Table 8: Conditions for behavior of harvesters under a per-unit tax τ_t on retained bycatch R_{1jYt}, and associated choice variables for each of the possible behaviors

Behavior	Conditions	e_{1jt}	R_{1jXt}	R_{1jYt}	D_{1jXt}	D_{1jYt}
No discards, full hold	$\tau_t^X \le \tau \le \tau_t^Y$	$\frac{\overline{R_1}}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}$	$\overline{R_1}\left(\frac{q_{1X}X_t}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}\right)$	$\overline{R_1}\left(\frac{q_{1Y}Y_t}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}\right)$	0	0
No discards, trip truncated	$\tau_t > \overline{\tau_t}$	0	0	0	0	0
Discard X for Y	$\tau_t < \tau_t^X$	$\frac{\overline{R_1}}{\theta_{1jt}q_{1Y}Y_t}$	0	$\overline{R_1}$	$\frac{\overline{R_1}q_{1X}X_t}{\theta_{1jt}q_{1Y}Y_t}$	0
Discard Y for X	$\tau_t^Y < \tau < \overline{\tau_t}$	$\frac{\overline{R_1}}{q_{1X}X_t}$	$\overline{R_1}$	0	0	$\frac{\overline{R_1}\theta_{1jt}q_{1Y}Y_t}{q_{1X}X_t}$

Table 9a: Conditions for behavior of harvesters under a trip limit τ_t on retained bycatch R_{1jYt}, and effort levels associated with each of the possible behaviors

Behavior	Conditions	e_{1jt}
No discards, full hold	$\tau_t \geq \overline{R_1}\left(\frac{\theta_{1jt}q_{1Y}Y_t}{\theta_{1jt}q_{1Y}Y_t + q_{1X}X_t}\right)$; $(1-\gamma)p_Y - p_X > MC_{1Y}$	$\frac{\overline{R_1}}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}$
No discards, trip truncated	$\tau_t < \overline{R_1}\left(\frac{\theta_{1jt}q_{1Y}Y_t}{\theta_{1jt}q_{1Y}Y_t + q_{1X}X_t}\right)$; $p_X \leq MC_{1X}$	$\frac{\tau_t}{\theta_{1jt}q_{1Y}Y_t}$
Discard X for Y	$\tau_t \geq \overline{R_1}\left(\frac{\theta_{1jt}q_{1Y}Y_t}{\theta_{1jt}q_{1Y}Y_t + q_{1X}X_t}\right)$ $(1-\gamma)p_Y - p_X > MC_{1Y}$	$\frac{\tau_t}{\theta_{1jt}q_{1Y}Y_t}$
Discard Y for X	$\tau_t < \overline{R_1}\left(\frac{\theta_{1jt}q_{1Y}Y_t}{\theta_{1jt}q_{1Y}Y_t + q_{1X}X_t}\right)$ $p_X > MC_{1X}$	$\frac{\overline{R_1} - \tau_t}{q_{1X}X_t}$

Table 9b: Catch retention and discard levels for each of the possible behaviors of a harvester under a trip limit τ_t on retained bycatch R_{1jYt}, and associated choice variables for each of the possible behaviors

Behavior	R_{1jXt}	R_{1jYt}	D_{1jXt}	D_{1jYt}
No discards, full hold	$\overline{R_1}\left(\frac{q_{1X}X_t}{q_{1X}X_t+\theta_{1jt}q_{1Y}Y_t}\right)$	$\overline{R_1}\left(\frac{\theta_{1jt}q_{1Y}Y_t}{q_{1X}X_t+\theta_{1jt}q_{1Y}Y_t}\right)$	0	0
No discards, trip truncated	$\tau_t\frac{q_{1X}X_t}{\theta_{1jt}q_{1Y}Y_t}$	τ_t	0	0
Discard X for Y	$\overline{R_1}-\tau_t$	τ_t	$\tau_t\left(1+\frac{q_{1X}X_t}{\theta_{1jt}q_{1Y}Y_t}\right)-\overline{R_1}$	0
Discard Y for X	$\overline{R_1}-\tau_t$	τ_t	0	$\left(\overline{R_1}-\tau_t\right)\left(1+\frac{\theta_{1jt}q_{1Y}Y_t}{q_{1X}X_t}\right)-\tau_t$

Table 10a: Conditions for behavior of harvesters under a value-based quota, and effort levels for each of the possible behaviors

Behavior	Conditions	e_{1jt}
No discards, full hold	$\overline{R_1}\left[\frac{p_X q_{1X} X_t + (1-\gamma) p_Y \theta_{1jt} q_{1Y} Y_t}{q_{1X} X_t + \theta_{1jt} q_{1Y} Y}\right] < \tau_t$; $(1-\gamma) p_Y - p_X < MC_{1Y}$	$\frac{\overline{R_1}}{q_{1X} X_t + \theta_{1jt} q_{1Y} Y_t}$
No discards, trip truncated	$\overline{R_1}\left[\frac{p_X q_{1X} X_t + (1-\gamma) p_Y \theta_{1jt} q_{1Y} Y_t}{q_{1X} X_t + \theta_{1jt} q_{1Y} Y}\right] > \tau_t$	$\frac{\tau_t}{p_X q_{1X} X_t + (1-\gamma) p_Y \theta_{1jt} q_{1Y} Y_t}$
Discard X for Y	$\overline{R_1}\left[\frac{p_X q_{1X} X_t + (1-\gamma) p_Y \theta_{1jt} q_{1Y} Y_t}{q_{1X} X_t + \theta_{1jt} q_{1Y} Y}\right] < \tau_t$; $(1-\gamma) p_Y - p_X > MC_{1Y}$	$\frac{\tau_t - \overline{R_1} p_X}{(1-\gamma) p_Y - p_X}$
Discard Y for X	---	---

Table 10b: Catch retention and discard levels for each of the possible behaviors of a harvester under a value-based quota.

Behavior	R_{1jXt}	R_{1jYt}	D_{1jXt}	D_{1jYt}
No discards, full hold	$\overline{R_1}\left(\frac{q_{1X}X_t}{q_{1X}X_t+\theta_{1jt}q_{1Y}Y_t}\right)$	$\overline{R_1}\left(\frac{\theta_{1jt}q_{1Y}Y_t}{q_{1X}X_t+\theta_{1jt}q_{1Y}Y_t}\right)$	0	0
No discards, trip truncated	$\frac{\tau_t q_{1X}X_t}{p_X q_{1X}X_t+(1-\gamma)p_Y\theta_{1jt}q_{1Y}Y_t}$	$\frac{\tau_t\theta_{1jt}q_{1Y}Y_t}{p_X q_{1X}X_t+(1-\gamma)p_Y\theta_{1jt}q_{1Y}Y_t}$	0	0
Discard X for Y	$\frac{\overline{R_1}(1-\gamma)p_Y-\tau_t}{(1-\gamma)p_Y-p_X}$	$\frac{\tau_t-\overline{R_1}p_X}{(1-\gamma)p_Y-p_X}$	$\frac{(\tau_t-\overline{R_1}p_X)q_{1X}X_t+\left[\overline{R_1}(1-\gamma)p_Y\right]\theta_{1jt}q_{1Y}Y_t}{\left[(1-\gamma)p_Y-p_X\right]\theta_{1jt}q_{1Y}Y_t}$	0
Discard Y for X	---	---	---	---

LITERATURE CITED

Allen, P. M. and J. M. MacGlade, 1986. Dynamics of discovery and exploitation: The case for the scotian shelf groundfish fisheries. *Canadian Journal of Fisheries and Aquatic Science* **43**: 1187-1200.

Alverson, D. L., 1999. Some observations on the science of bycatch. *Marine Technology Society Journal* **33**(2): 6-12.

Alverson, D. L., M. H. Freeberg, et al., 1994. A global assessment of fisheries bycatch and discards. *FAO Fisheries Technical Paper* **339**.

Anderson, L. G., 1999. The microeconomics of vessel behavior: A detailed short-run analysis of the effects of regulation. *Marine Resource Economics* **14**: 129-150.

Androkovich, R. A. and K. R. Stollery, 1992. A stochastic dynamic programming model of bycatch control in fisheries. *Marine Resource Economics* **9**(2): 19-30.

Arnason, R., 1994. On catch discarding in fisheries. *Marine Resource Economics* **9**(3): 189-207.

Beddington, J. R. and R. M. May, 1980. Maximum sustainable yields in systems subject to harvesting at more than one trophic level. *Mathematical Biosciences* **51**: 261-281.

Beverton, R. J. H. and S. J. Holt, 1957. On the dynamics of exploited fish populations. *FAO Fisheries Investigations* **2**(19): 1-537.

Boyce, J. R., 1996. An economic analysis of the fisheries bycatch problem. *Journal of Environmental Economics and Management* **31**: 314-336.

Brown, G., 2000. Renewable natural resource management and use without markets. *Journal of Economic Literature* **38**: 875-914.

Brown, G. and J. Roughgarden, 1997. A metapopulation model with private property and a common pool. *Ecological Economics* **22**(1): 65-71.

Caddy, J. F., 1975. Spatial model for an exploited shellfish population, and its application to the georges bank scallop fishery. *Journal of Fisheries Research Board of Canada* **32**: 1305-1328.

Chaudhuri, K. S., 1986. A bioeconomic model of harvesting a multispecies fishery. *Ecological Modelling* **32**: 267-279.

Chaudhuri, K. S., 1987. Dynamic optimization of combined harvesting of a two-species fishery. *Ecological Modeling* **41**: 17-25.

Clark, C. W., 1990. *Mathematical bioeconomics: The optimal management of renewable resources*. New York, Wiley & Sons.

Day, J. R. and H. P. Possingham, 1995. A stochastic metapopulation model with variability in patch size and position. *Theoretical Population Biology* **48**(3): 333-360.

Defeo, O., J. C. Sedo, et al., 1991. Spatial dynamics of fishing effort in an artisanal fishery of the uruguayan coast. *Investigacion pesquera (Chile)* **36**: 17-25.

Fahrig, L., 1993. Effect of fish movement and fleet spatial behavior on management of fish stocks. *Natural Resource Modeling* **7**(1): 37-56.

Fletcher, J. J., R. E. Howitt, et al., 1988. Management of multipurpose heterogeneous fishing fleets under uncertainty. *Marine Resource Economics* **4**(4): 249-270.

Gordon, H. S., 1954. The economic theory of a common property resource: The fishery. *Journal of Political Economy* **62**: 124-142.

Hall, M. A., 1996. On bycatches. *Review of Fish Biology and Fisheries* **6**(3): 319-352.

Hardin, G., 1968. The tragedy of the commons. *Science* **162**: 1243-1248.

Hartman, R., 1976. The harvesting decision when a standing forest has value. *Economic Inquiry* **14**: 52-68.

Hilborn, R. and R. B. Kennedy, 1992. Spatial patterns in catch rates: A test of economic theory. *Bulletin of Mathematical Biology* **54**(2/3): 263-273.

Hoagland, P. and D. Jin, 1997. A model of bycatch involving a passive use stock. *Marine Resource Economics* **12**: 11-28.

Jacobson, L. D., J. Brodziak, et al., 1997. Empirical fishery selectivity estimates for dover sole, sablefish, and thornyheads in the deep water dover fishery. *Unpublished draft report.*

Jacobson, L. D. and J. R. Hunter, 1993. Bathymetric demography and management of dover sole. *North American Journal of Fisheries Management* **13**(3): 405-420.

Jacobson, L. D. and R. D. Vetter, 1996. Bathymetric demography and niche separation of thornyhead rockfish: *Sebastolobus alascanus* and *sebastolobus altivelis*. *Canadian Journal of Fisheries and Aquatic Science* **53**: 600-609.

Kirkley, J. and I. E. Strand, 1988. The technology and management of multispecies fisheries. *Applied Economics* **20**: 1279-1292.

McCaughran (1992). *Standardized nomenclature and methods of defining bycatch levels and implications*. National Industry Bycatch Workshop, Newport, OR, Natural Resources Consultants.

McKelvey, R., 1983. The fishery in a fluctuating environment: Coexistence of specialist and generalist fishing vessels in a multipurpose fleet. *Journal of Environmental Economics and Management* **10**: 287-309.

Mesterton-Gibbons, M., 1987. On the optimal policy for combined harvesting of independent species. *Natural Resource Modeling* **2**(1): 109-134.

Mesterton-Gibbons, M., 1988. On the optimal policy for combined harvesting of predator and prey. *Natural Resource Modeling* **3**: 63-90.

Mesterton-Gibbons, M., 1996. A technique for finding optimal two-species harvesting policies. *Ecological Modeling* **92**(2-3): 235-244.

Muse, B. and K. Schelle, 1989. Individual fisherman's quotas: A preliminary review of some recent programs, Alaska Commercial Fisheries Entry Commission.

Natural_Resource_Consultants, 1990. The nature and scope of fishery-dependent mortalities in the commercial fisheries of the northeast pacific. Seattle.

Opaluch, J. J. and N. E. Bockstael, 1984. Behavioral modeling and fisheries management. *Marine Resource Economics* **1**: 105-115.

Pascoe, S., 2000. Single species conservation in a multispecies fishery: The case of the Australian eastern gemfish. *Ecological Economics* **32**: 125-136.

Ragozin, D. L. and G. Brown, 1985. Harvest policies and nonmarket valuation in a predator-prey system. *Journal of Environmental Economics and Management* **12**: 155-168.

Sanchirico, J. N. and J. E. Wilen, 1999. Bioeconomics of spatial exploitation in a patchy environment. *Journal of Environmental Economics and Management* **37**(2): 129-150.

Squires, D. and J. Kirkley, 1991. Production quota in multiproduct pacific fisheries. *Journal of Environmental Economics and Management* **21**: 109-126.

Supriatna, A. K. and H. P. Possingham, 1999. Harvesting a two-patch predator-prey metapopulation. *Natural Resource Modeling* **12**(4): 481-497.

Tuck, G. N. and H. P. Possingham, 1994. Optimal harvesting strategies for a metapopulation. *Bulletin of Mathematical Biology* **56**(1): 107-127.

Turner, M. A., 1996. Value-based itqs. *Marine Resource Economics* **11**: 59-69.

Turner, M. A., 1997. Quota-induced discarding in heterogeneous fisheries. *Journal of Environmental Economics and Management* **33**: 186-195.

Underwood, A. J. and P. G. Fairweather, 1989. Supply-side ecology and benthic assemblages. *TREE* **4**(1): 16-20.

Vestergaard, N., 1996. Discard behavior, highgrading, and regulation: The case of the Greenland shrimp fishery. *Marine Resource Economics* **11**: 247-266.

Vestergaard, N., 1999. Measures of welfare effects in multiproduct industries: The case of multispecies individual quota fisheries. *Canadian Journal of Economics* **32**(3): 729-743.

Wilen, J. E., 2000. Renewable resource economists and policy: What differences have we made? *Journal of Environmental Economics & Management* **39**(3): 306-327.

Wilson, J. A., 1982. The economical management of multispecies fisheries. *Land Economics* **58**(4): 417-434.

Yew, T. S. and T. Heaps, 1996. Effort dynamics and alternative management policies for the small pelagic fisheries of northwest peninsular Malaysia. *Marine Resource Economics* **11**: 85-103.

APPENDIX: SOLUTION TO HARVESTER LP PROBLEM UNDER A TAX ON BYCATCH

During a given time period, all harvesters act as "stock takers," i.e. they assume that stock levels are exogenous to their harvest decisions (and those of others). Under this assumption, it follows that a given harvester j in F1 harvests fully, so that $R_{1jXt} + R_{1jYt} = \overline{R_1}$, as long as the marginal net benefit of effort is positive:

$$p_{1X} q_{1X} X_t + \left[(1-\gamma) p_Y - \tau_t \right] \theta_{1jt} q_{1Y} Y_t - c_1 > 0 \tag{48}$$

A tax in excess of

$$\overline{\tau_t}(X_t, Y_t) = \frac{p_{1X} q_{1X} X_t + (1-\gamma) p_Y \theta_{1jt} q_{1Y} Y_t - c_1}{\theta_{1jt} q_{1Y} Y_t} \tag{49}$$

causes F1 harvesters to shut down.

If a given harvester does operate, the hold contains the following amounts of X and Y:

$$\begin{aligned} R^0_{1jXt} &= \overline{R_1} \left(\frac{q_{1X} X_t}{q_{1X} X_t + \theta_{1jt} q_{1Y} Y_t} \right) \\ R^0_{1jYt} &= \overline{R_1} \left(\frac{\theta_{1jt} q_{1Y} Y_t}{q_{1X} X_t + \theta_{1jt} q_{1Y} Y_t} \right) \end{aligned} \tag{50}$$

The effort required to thus fill the hold initially is

(51) $$e^0_{1jt} = \frac{\overline{R_1}}{q_{1X}X_t + \theta_{1jt}q_{1Y}Y_t}$$

A harvester j finds it profitable to discard Y in order to retain more X if the benefits, net of harvest costs, of doing so are positive, i.e. if $p_X - \left[(1-\gamma)p_Y - \tau_t\right] > MC_{1jXt}$. Combining this condition with (35) implies that harvesters discard Y in favor of X if $\tau^Y_t < \tau_t \leq \overline{\tau_t}$, where

(52) $$\tau^Y_t(X_t, Y_t) = \frac{c_1}{q_{1X}X_t} - p_X + (1-\gamma)p_Y .$$

If they do discard Y for X, they retain $R_{1jXt} = \overline{R_1}$, $R_{1jYt} = 0$. Total effort required for such a vessel to fill the hold exclusively with X is

(53) $$e_{1jt} = \frac{\overline{R_1}}{q_{1X}X_t},$$

and total discards by vessel j are

(54) $$D_{1jXt} = 0$$
$$D_{1jYt} = \frac{\overline{R_1}\theta_{1jt}q_{1Y}Y_t}{q_{1X}X_t} .$$

Harvesters discard in the other direction, i.e. discarding X in favor of Y, if $\left[(1-\gamma)p_Y - \tau_t\right] - p_X > MC_{1jYt}$. From (35), this implies discarding of X if $\tau_t < \tau^X_t$ where

$$(55) \qquad \tau_t^X(X_t, Y_t) = (1-\gamma)p_Y - p_X - \frac{c_1}{\theta_{1jt} q_{1Y} Y_t}.$$

Vessels that discard Y for X retain $R_{1jXt} = 0$, $R_{1jYt} = \overline{R_1}$. Total effort required for such a vessel to fill the hold exclusively with X is

$$(56) \qquad e_{1jt} = \frac{\overline{R_1}}{\theta_{1jt} q_{1Y} Y_t},$$

and total discards by vessel j are

$$(57) \qquad \begin{aligned} D_{1jXt} &= \frac{\overline{R_1} q_{1X} X_t}{\theta_{1jt} q_{1Y} Y_t}. \\ D_{1jYt} &= 0 \end{aligned}$$

The different behaviors as functions of τ_t are illustrated as non-overlapping subsets of the parameter space T in Figure 11. The critical levels of τ_t that cause shifts in behavior are functions of the time t stock levels X_t and Y_t. There are no non-negativity constraints on these critical levels; it could be the case that a subsidy on bycatch, i.e. $\tau_t < 0$, is required to elicit discarding of X in favor of Y or even, in extreme cases, to prevent shutdown of F1. The conditions for each of the four potential harvester behaviors is summarized in Table 8.

The effort levels corresponding to the two types of discarding behavior are unequivocally larger than that arising with no discarding. This is an intuitive result of the fact that, under selective retention of either X or Y, the same hold capacity $\overline{R_1}$ is filled with a smaller marginal product of effort, in terms of retained tons per unit of effort exerted.

VITA

Guillermo (Ta) Herrera was born and raised in Newton Highlands, Massachusetts. He attended Newton South High School before attending Harvard College, where he received an A.B. in Biology in 1989. After a brief hiatus, he then attended the University of Washington in Seattle, where he received an M.S. from the Quantitative Ecology and Resource Management (QERM) program in 1998 and a Ph.D. from the Department of Economics in 2001. Ta currently resides in Brunswick, Maine, where he is a faculty member in the Department of Economics at Bowdoin College.